RENTECH Incorporated
2503 Artie Street, Suite 21
Huntsville, Alabama 35805

(1)

(14) RTR-013-1-Vol-I

AD917385

(6) A COMPUTER PROGRAM FOR THE PREDICTION OF RADIATION FROM ROCKET EXHAUST PLUMES.

Volume I

(11) 31 May 1973

(12) 95p.

(10) by JOHN E. REARDON

(15) Prepared under Contract DAAH01-73-C-0252
for
U. S. Army Missile Command
Redstone Arsenal Alabama 35809

B

DISPOSITION INSTRUCTIONS

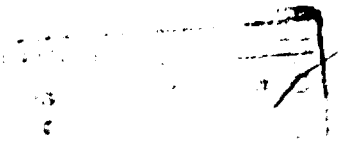
DESTROY THIS REPORT WHEN IT IS NO LONGER NEEDED. DO NOT RETURN IT TO THE ORIGINATOR.

DISCLAIMER

THE FINDINGS IN THIS REPORT ARE NOT TO BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION UNLESS SO DESIGNATED BY OTHER AUTHORIZED DOCUMENTS.

TRADE NAMES

USE OF TRADE NAMES OR MANUFACTURERS IN THIS REPORT DOES NOT CONSTITUTE AN OFFICIAL INDORSEMENT OR APPROVAL OF THE USE OF SUCH COMMERCIAL HARDWARE OR SOFTWARE.



SUMMARY

This report describes a program for predicting infrared radiation from rocket exhaust gases to a point using a statistical band model with a wavenumber interval of 25 cm^{-1}. Absorption coefficient data for water vapor, carbon dioxide, carbon monoxide, hydrogen chloride, hydrogen flouride, and soot (carbon particles) are included in the program data statements. Provision has been made for the future addition of one additional radiating species. Input for the program is gas property data (temperature, pressure, and constituent mole fractions) in either an axisymmetric or three-dimensional cylindrical coordinate system. The program can integrate the radiation from the gas to a point to provide overall radiation as well as spectral distribution of radiation at intervals of 25 cm^{-1}. In addition, detailed optical data can be provided at each spectral interval when only a single line of sight through the gas is considered.

CONTENTS

VOLUME I

VOLUME II

INTRODUCTION

Accurate prediction of infrared radiation from rocket exhaust plumes has important applications in prediction of heat transfer from the exhaust to surrounding structure and in definition of the spectral distribution of radiation which may be used for detecting and tracking rocket vehicles. The computer program described here is a modification of one originally developed by NASA/MSFC* to predict radiant transfer to the base region of rocket vehicles. It was necessary to use band model prediction methods with relatively narrow spectral intervals for the exhaust plume thermal radiation to provide proper representation of the inhomogeneous plumes. As a result, the program also provides spectral data which may be useful in predicting detectability of rocket powered vehicles.

The primary modification to the original NASA/MSFC program was the addition of hydrogen chloride and hydrogen fluoride radiation calculations to those already existing for water vapor, carbon dioxide, carbon monoxide, and carbon particles. In addition, several minor changes were made to the program to correct small errors, incorporate some more recent recommendations of line half-width parameters, and adapt the program to the CDC 6600 computer.

A description of the analytical methods used and the general program operation is presented in the body of the report and detailed information such as a definition of terms, input/output formats, a program listing, and a sample problem are included in appendices.

---

* The program modified was Job Number 353887 obtained from Computation Laboratory, George C. Marshall Space Flight Center.

TECHNICAL DISCUSSION

The computer program uses input gas property data (temperature, pressure, and gas constituent mole fractions) along with geometric data locating a point of interest relative to the gas. Lines of sight from the point of interest are directed through the gas at intervals specified in the input. Then radiation along these lines of sight is computed and the results are spatially integrated to produce the resultant radiant flux (watts/cm^2) at the point of interest. The discussion presented in this section will describe the analytical basis for the solution and the numerical methods used.

DESCRIPTION OF THE PROBLEM

The geometry used to describe the problem consists of two coordinate systems as illustrated in Figure 1. The gas properties are defined at locations in a cylindrical coordinate system relative to the left-hand X, Y, Z coordinate system. For axisymmetric exhaust plumes, the Z-axis is the center of the cylindrical system for the gas flow field, and properties are defined at points located by r and Z. (Computer programs for preparing input tapes for axisymmetric flow fields are described in Refs. 1 and 2). For three-dimensional exhaust plumes, options are available to simplify the flow field input by using symmetry which may exist in the flow field. These options allow the axis of the cylindrical coordinate system to be moved from the Z-axis (see Special Option 21), but in the general three-dimensional, the gas properties are defined about the Z-axis at points located by r, Z, and the angle η (where η is a positive angle measured from the X-axis and increasing in the counter-clockwise direction

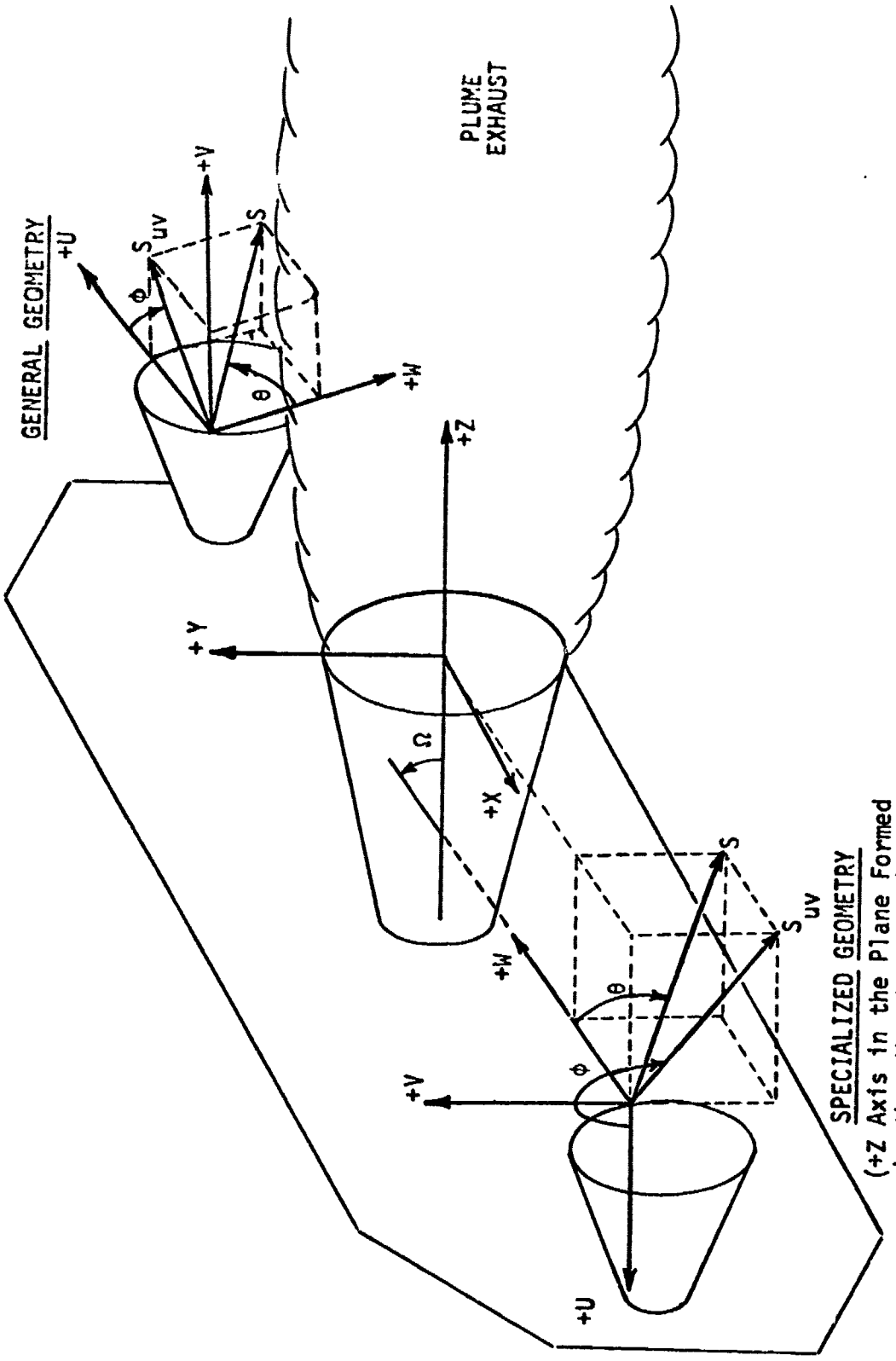


Figure 1. Illustration of Radiation Computer Program Geometry.

when viewed from $Z = -\infty$).

The point of interest at which the radiation transfer is to be computed is the center of a right-hand U, V, W coordinate system in which W is the surface normal. The point is located by its coordinates (X_p, Y_p, Z_p) and the orientation of the surface is defined in general by specifying the nine directions cosines defining the direction of the U, V, W axes with respect to the X, Y, Z axes. A simpler input method is provided in which only a single angle, Ω, defining the surface rotation is specified, but this method is limited to surface elements which are oriented as though they were on surfaces of revolution about the Z-axis (see Special Option 4).

Radiant flux to the point of interest is calculated using a spherical coordinate system in which the inclination of a line of sight to the surface normal (W) is the angle θ, while the azimuth angle between the projection of the line of sight (s) in the U-V plane and the U-axis is ϕ (see Figure 1). The heat transfer equation used to describe the radiation to the point of interest in the spectral region between wavenumbers ω_i and ω_f is

$$\dot{q}/A = \int_{\theta_i}^{\theta_f} \int_{\phi_i}^{\phi_f} \int_{\omega_i}^{\omega_f} \int_{0}^{L} - N^{\circ}_{\omega} \left(\frac{d\tau(s,\omega)}{ds} \right) ds \, d\omega \, d\phi \cos\theta \sin\theta \, d\theta, \quad (1)$$

where τ is the transmissivity of the gas and N°_{ω} is the Planck Function. The equation describes the radiation from the gas integrated over a portion of a hemisphere (depending on ϕ and θ limits) of radius L centered at the point of interest. No provision is made for radiation entering the gas from

other sources.

The transmissivity is determined from

$$\tau\ (s,\omega) = \exp\ \left[-\ X\ (s,\omega)\right], \tag{2}$$

where $X(s,\omega)$ is the optical depth of the gas mixture. In the general case of multiple radiating species, the optical depth is the sum of the optical depths of the i radiating species in the gas mixture

$$X(s,\omega) = \sum_i X(s,\omega,i). \tag{3}$$

The method used for predicting the optical depth depends on the species considered. Gaseous species are described by statistical (random) band models while carbon particles are treated using a model similar to Beer's law.

The development of the band models used in the computer program have been described in References 5 through 8 and the recommend procedures and data are summarized in Reference 9. The curve of growth of the optical depth as a function of path length, u, is represented for collision broadened (Lorentz) lines in an isothermal gas by

$$X(T,p,p_i,s,\omega,\ i) = k(T,\omega,i)\ u(T,p_i,s)/\{1+k(T,\omega,i)u(T,p_i,s)/ [4\gamma_c\ (T,p,p_i)/d(T,\omega,i)]\}^{-1/2} \tag{4}$$

where k is the absorption coefficient, γ_c is the line half-width, d is the line spacing, p is the pressure, p_i is the partial pressure of the radiating gas, and T is the gas temperature. The functional notation used in Eq. (4) is cumbersome and will be eliminated from further equations except where required for clarity. However, it is useful at this point to clarify the

definition of terms as used in the analysis. The absorption coefficient used is defined for a homogeneous gas by

$$k = \lim_{u \to 0} \left[(- \ln \tau)/u\right], \tag{5}$$

where u is the equivalent optical path at standard temperature and pressure,

$$u = s(cm) \left[\frac{p(atm)}{1\ atm} \frac{273K}{T(K)}\right] . \tag{6}$$

The absorption coefficient used in the computer program is an average value representing the equivalent absorption in a 25 cm^{-1} wavenumber interval, so fine spectral details cannot be reproduced using the program. This spectral averaging over a small wavenumber interval is implied in all the equations describing the band models although no special notation is used to denote an average value except in the case of spatial averaging over an inhomogeneous path. The only monochromatic value used in the program is the Plank function, N°_{ω}.

The line half-width is treated as a function of temperature, partial pressure of the radiating constituent, and partial pressures of all the other constituents. Dependence of the fine structure parameter

$$a_c = \gamma_c / d \tag{7}$$

on wavenumber is accounted for by the line spacing d which is a function of temperature and wavenumber for each constituent.

The curve of growth represented by Eq. (4) has the limits

$$X = ku \tag{8}$$

for small values of u ($ku \ll 4\gamma/d$), and

$$X = (4\, ku\, \gamma_c/d)^{1/2} \qquad (9)$$

for large values of u ($ku \gg 4\gamma/d$). These are referred to as the weak line and strong line limits which are characteristic of isolated Lorentz lines as well as several statistical band models. The behavior of Eq. (4) between the limits accurately represents a band model composed of randomly located lines in which the probability of occurance of a given line strength is proportional to exp(- line strength). This is the so-called "Goody" model, and widespread use of this model results not so much from any rational physical basis as from the fact that the expression for the curve of growth has a simple algebraic form. It is also a reasonable approximation of other statistical band models. For example, Eq.(4) represents the curve of growth for a spectrum of equal strength randomly located lines with a maximum error of 8 percent.

Caution should be exercised in using the statistical band model representation to describe gases with relatively regular line spacing such as HCl and HF. If the results obtained do not appear to compare well with measured data, consideration should be given to using the Elsasser model which assumes a uniform spacing of equally strong Lorentz lines.

The optical depth due to Doppler broadening is also modeled using a random band model. The expression used[1] is a mathematical approximation (within 10 percent) of the curve of growth which results from a random distribution of equal strength Doppler lines. For conditions in which both collision and Doppler broadening are important, a form is provided[2]

---

1. See Table 1, Eq. (17a)
2. See Table 1, Eq. (14a)

approximating a line having combined Lorentz and Doppler broadening.

In the discussion of band models up to this point, only homogenous gases have been considered. The models are applied to inhomogenous gases through a modification of the Curtis-Godson approximation which was originally proposed for a single line. The method used in the program replaces ku with an integrated optical depth for the weak line limit

$$X^* = \int_0^u k\,du' \tag{10}$$

and averages the fine structure parameter weighed by the product ku,

$$\bar{a} = \frac{1}{X^*} \int_0^u \frac{\gamma}{d}\, k\,du'. \tag{11}$$

This method of averaging has been shown experimentally to give good results over moderate ranges of temperature and absorption (Ref. 10) , but it may be expected to produce errors in some extreme cases. In particular, when there are large temperature variations along a line of sight so that radiation from a hot gas layer must pass through a relatively massive cold gas layer, errors are likely to be significant. Fortunately, the isentropic expansion in rocket exhaust plumes produces extremely low pressures in low temperature regions, so the mass of cool layers tends to be small.

In order to provide a more exact representation of the effects encountered with drastic temperature variations as well as a simpler method for less demanding conditions, two forms of band models are used in

the computer program. The more exact representation uses a superposition of a number of line groups to account for the additional line positions as higher vibrational states are excited at high temperatures, while the simpler representation neglects the appearance of new lines. The existing program nomenclature of Model 3 and Model 3A for these two methods will be retained in this discussion without attempting to describe the history of the numbering system. All the relations comprising the two models are listed in Table 1, and the required line width parameters are presented in Table 2.

The θ term in Eq. (20) (Table 1) represents the energy associated with a vibrational transition, so the $\exp(-\theta n/T)$ term represents a measure of the probability of shifted line positions (due to vibrational transitions) as a function of the gas temperature. The form of the absorption coefficient for Model 3 reduces to that for Model 3A as θ goes to infinity, and the $1/d$ values for the two models are formulated to give the same optical depth in the strong line limit. If T is somewhat less than θ, the usual result is that radiance predicted by Model 3 is less than Model 3A. This is caused by the reduction in optical depth due to the reduced line density of Model 3 being more significant than the increases due to the added line groups.

Although Table 1 indicates that Model 3 consists of an infinite number of line groups, only a few groups are required in practice. Inspection of Eq. (20) (Table 1) indicates that the exponential term will become negligible compared to the first term at small values of n if the gas temperature is within the range of the absorption coefficient data ($T \leq 3000K$). Because of this, the computer program has been arranged to handle only 10 line groups (n = 0 to 9) to reduce storage requirements.

The functions used to relate $1/d$ and $1/d_0$ are derived by equating the

TABLE 1. COMPARISON OF MODELS 3 AND 3A

Parameter	Model 3	Model 3A
Optical Depth of all Line Grcups	$X = \sum_{n=0}^{\infty} X_n$ (12)	Not Applicable
Optical Depth	$X_n = \sqrt{1 - Y_n^{-1/2}}\, X_n^*$ (13)	$X = \sqrt{1 - Y^{-1/2}}\, X$ (13a)
Combined Collision and Doppler Optical Depths	$Y_n = \left[1 - \left(\frac{X_{cn}}{X_n}\right)^2\right]^{-2} + \left[1 - \left(\frac{X_{Dn}}{X_n^*}\right)^2\right]^{-2} - 1$ (14)	$Y = \left[1 - \left(\frac{X_c}{X^*}\right)^2\right]^{-2} + \left[1 - \left(\frac{X_D}{X^*}\right)^2\right]^{-2} - 1$ (14a)
Optical Depth for the Weak Line Limit	$X_n^* = \int_0^u k_n du'$ (15)	$X^* = \int_0^u k_{STP} du'$ (15a)
Optical Depth for a Pure Collision Curve of Growth	$X_{cn} = X_n^* \left[1 + X_n^*/4\bar{a}_{cn}\right]^{-1/2}$ (16)	$X_c = X^* \left[1 + X^*/4\bar{a}_c\right]^{-1/2}$ (16a)

TABLE 1. (Continued)

Parameter	Model 3	Model 3A
Optical Depth for a Pure Doppler Curve of Growth	$X_{Dn} = 1.7\bar{a}_{Dn}\sqrt{\ln\left[1+\left(\frac{X_n^*}{1.7\bar{a}_{Dn}}\right)^2\right]}$ (17)	$X_D = 1.7\bar{a}_D\sqrt{\ln\left[1+\left(\frac{X^*}{1.7\bar{a}_D}\right)^2\right]}$ (17a)
Collision Broadened Fine Structure Parameter	$\bar{a}_{cn} = \frac{1}{X_n^*}\int_0^u \frac{\gamma_c}{d_n} k_n du'$ (18)	$\bar{a}_c = \frac{1}{X^*}\int_0^u \frac{\gamma_c}{d} k_{STP} du'$ (18a)
Doppler Broadened Fine Structure Parameter	$\bar{a}_{Dn} = \frac{1}{X_n^*}\int_0^u \frac{\gamma_D}{d_n} k_n du'$ (19)	$\bar{a}_D = \frac{1}{X^*}\int_0^u \frac{\gamma_D}{d} k_{STP} du'$ (19a)

TABLE 1. (Continued)

Parameter	Model 3	Model 3A
Absorption Coefficient for the nth Line Group $(cm^{-1})_{STP}$	$k_n = k_{STP} \dfrac{f_n \exp(-\theta n/T)}{\sum_{n=0}^{\infty} f_n \exp(-\theta n/T)}$ f_n / θ(K) H_2O: 1 / 2300 CO_2: 1 / 960 CO: n+1 / 3123 HCl: n+1 / 4170 HF: n+1 / 5950	Not Applicable
Line Density (cm)	$1/d_n = g_n/d_o$ (21) Species / g_n / $1/d_o$ H_2O: 1 / See Eq. 23 CO_2: $(1+\varepsilon n)^2$ / $1/d_o$ is tabulated as a function of ω and T, and ε is included in the radiation calculation. See note at the end of this table.	For H_2O 1/d is tabulated as a function of ω and T, but an approximate mathematical expression is used if IFIN (1) $\leq$ 0. $1/d = \exp 0.7941 \sin(0.0036\omega - 8.043) + D(T)$ $D(T) = -2.294 + 0.3004 \times 10^{-2} T - 0.366 \times 10^{-6} T^2$ For CO_2, HCl, and HF 1/d is tabulated as a function of ω and T

TABLE 1. (Continued)

Parameter	Model 3	Model 3A
Line Density (cm)(continued)	Species g_n $1/d_o$ CO 1 0.29 For HCl and HF Eq. 22 or the approximation in Eq. 24 with 1/d taken from the tabulated value for Model 3A	For CO 1/d is determined by the approximation $1/d = 0.29 \frac{[1+\exp(-\theta/2T)]^{1.75}}{[1-\exp(-\theta/2T)]}$
Band Averaged Absorption Coefficient (cm^{-1}) For the ith Species	The coefficient k_{STP} for standard density is tabulated as a function of wavenumber and temperature.	
Optical Thickness for the ith Species (cm_{STP})	$u_i = p_i\ (273/T)s$ where p_i is the partial pressure of the ith species in atm, and s is the physical pathlength in cm	

TABLE 1. (Continued)

Parameter	Both Model 3 and Model 3A
Collision Half-Width (cm^{-1}) for the ith species. Broadening species denoted by j. Partial pressures p_i and p_j are in atmospheres.	$$\gamma_{c_i} = \left[\sum_j (\gamma_{i,j})_{273} p_j (273/T)^{n_{i,j}}\right] + (\gamma_{i,j\ 273} p_i (273/T)^{n_{i,i}} \quad (20)$$ See Table 2 for values of $\gamma_{i,j}$, $n_{i,j}$, $\gamma_{i,i}$, and $n_{i,i}$.
Doppler Half-Width (cm^{-1})	$$\gamma_{D_i} = (5.94 \times 10^{-6}) \frac{\omega}{m_i^{1/2}} (T/273)^{1/2} \quad (21)$$ where m_i = molecular wt. of ith species

Note: The program contains values of 1/d for CO_2 to be used in Model 3A only. If Model 3 is to be used the 1/d values must be modified to those given in Ref. 6 as indicated in Special Option 15.

TABLE 2

VALUES FOR THE COLLISION
BROADENING LINE WIDTH PARAMETERS (a)

Molecule (1)	Broadener (j)	$(\gamma_{i,j})_{273}$ $cm^{-1}atm^{-1}$	$n_{i,j}$	$(\gamma_{i,i})_{273}$ $cm^{-1}atm^{-1}$	$n_{i,i}$
H_2O	H_2O	(0.09)	0.5	0.44	1.0
	N_2	0.09	0.5		
	O_2	0.04	0.5		
	H_2	(0.05)	0.5		
	CO_2	0.12	0.5		
	CO	(0.10)	0.5		
	Other (b)	(0.05)	0.5		
CO_2	CO_2	0.09	0.5	0.01	1.0
	H_2O	(0.07)	0.5		
	N_2	0.07	0.5		
	O_2	0.055	0.5		
	H_2	0.08	0.5		
	CO	(0.06)	0.5		
	Other (b)	(0.08)	0.5		
CO	CO	0.06	0.5	0.0	1.0
	H_2O	(0.06)	0.5		
	CO_2	(0.07)	0.5		
	H_2	0.06	0.5		
	N_2	0.06	0.5		
	O_2	0.05	0.5		
	Other (b)	(0.06)	0.5		
HCl	HCl	(0.05)	0.5	0.15	1.0
	Other (b)	(0.05)	0.5		
HF	HF	(0.05)	0.5	0.45	1.0
	Other (b)	(0.05)	0.5		

NOTE: (a) Values in parenthesis are estimated.
(b) Values for other gases listed here are used in the program, but they may be modified using input Card 25.

optical depth of Model 3 and Model 3A in the strong line limit. This gives

$$1/d = 1/d_o \left\{ \left[\sum_{n=0}^{\omega} g_n^{1/2} f_n^{1/2} \exp(-\theta n/2T) \right]^2 \Big/ \sum_{n=0}^{\infty} f_n \exp(-\theta n/T) \right\} \qquad (22)$$

which, with suitable manipulation, becomes

$$1/d = 1/d_o \left\{ \left[1+\exp(-\theta/2T) \right] \Big/ \left[1-\exp(-\theta/2T) \right] \right\} \qquad (23)$$

for $f_n = g_n = 1$. For the case of $f_n = n+1$ and $g_n = 1$, Eq. (22) may be approximated within 3 percent by

$$1/d = 1/d_o \left\{ \left[1+\exp(-\theta/2T) \right]^{1.75} \Big/ \left[1-\exp(-\theta/2T) \right] \right\} \qquad (24)$$

The data used in the computer program for the band model parameters k, γ, and 1/d are based on a combination of experiments, analyses, and estimates based on the expected characteristics of the gaseous radiators. The collision half-width parameters listed in Table 2 are a combination of experimental and estimated values (Ref. 9). Values of k and 1/d for water vapor in the areas of primary importance were determined by fitting the band model for collision broadening to experimental measurements (Refs. 7 and 11). In regions where no data were obtained, estimates of the radiation behavior were made. Values of k and 1/d for the remaining gases are based primarily on theoretical predictions of the detailed line structure which is fitted by the band model (Refs. 5, 6, and 9). (It should be noted that temperature and wavenumber dependent values for 1/d for CO are available

(Ref. 9), but these have not been incorporated in the computer program).

Investigations of the carbon particles occuring in rocket exhausts (Refs. 3 and 4) indicated that the particles were so small that scattering effects were not significant for problems of heat transfer from exhaust plumes. Because of this, scattering has been neglected in the computer program, and carbon particles are treated as continuum radiators following a Beer's law model using experimentally determined values of the absorption coefficient. The optical depth for carbon particles is

$$X_c = \int_0^s k_c \rho_c ds'$$

where k_c is the absorption coefficient per unit density and path length (cm^2/gm), ρ_c is the local carbon particle density per unit gas volume (gm/cm^3), and s is the path length (cm).

Experimental values of the absorption coefficient (illustrated in Fig. 2) could only be determined over the wavelength range from 1 μm to 4 μm (2500 cm^{-1} to 10,000 cm^{-1} wavenumbers). Since serious errors could result in heat transfer by limiting calculations to this range, the data were extrapolated following the trends in the data to cover a range from 1 μm to 10 μm (1000 cm^{-1} to 10,000 cm^{-1}). The absorption coefficient data is stored in the program as polynomials which are functions of wavenumber for each the temperatures indicated in Fig. 2.

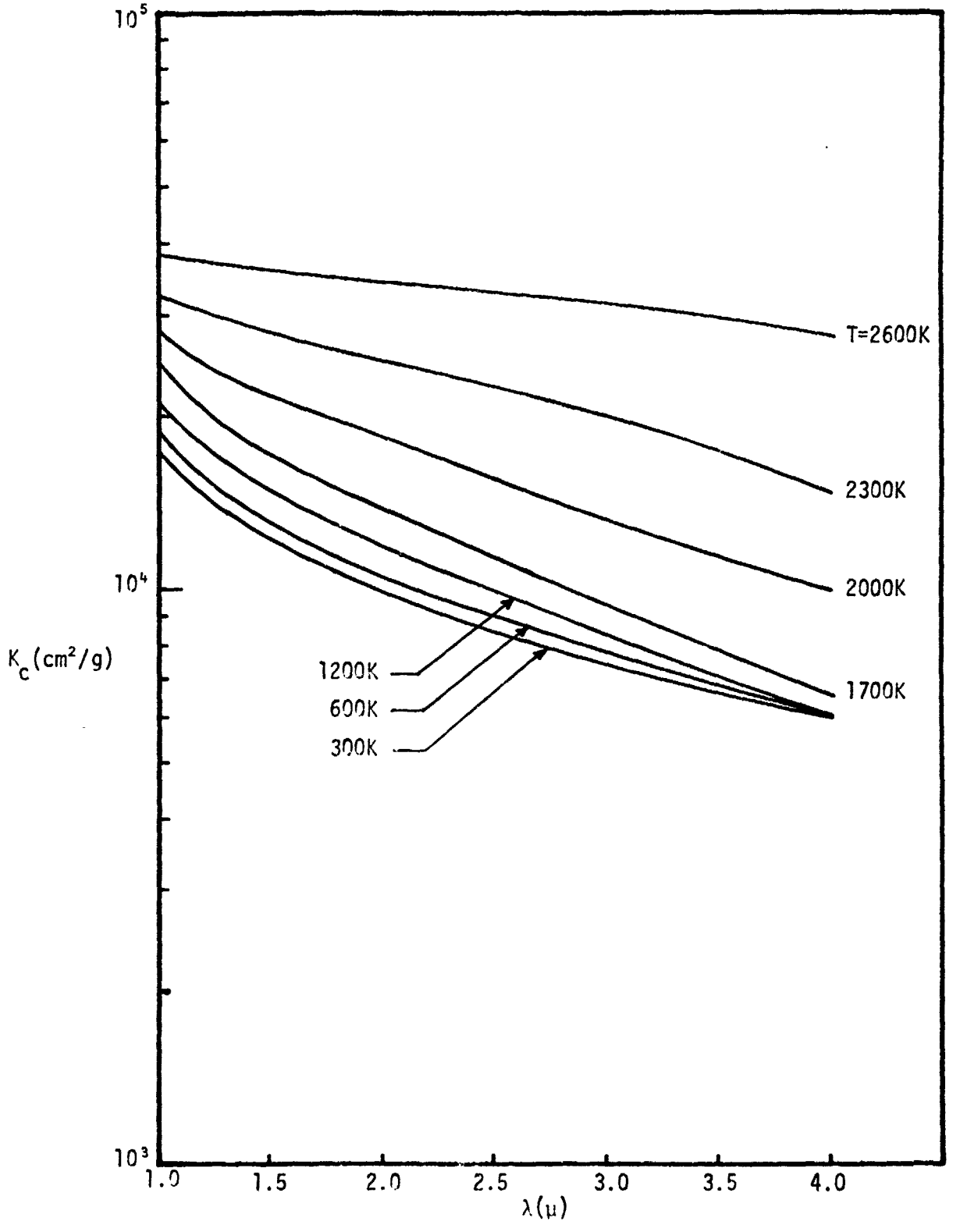


Figure 2. Results of the experimental determination of the carbon absorption coefficients. (Ref. 3)

NUMERICAL METHODS OF SOLUTION

The numerical techniques used in the program are relatively straightforward. The gas properties are determined at points along lines of sight by interpolation in the input gas data, and the radiation along each line of sight is computed using summations to represent the integration procedure described in the previous section.

Computations along the lines of sight begin with the line represented by the lower limits of the θ and ϕ integration ($\theta = \theta_i + \Delta\theta/2$ and $\phi = \phi_i + \Delta\phi/2$). The sequence of processing the lines carries through all values of ϕ before starting with the next interval of θ at the minimum value of ϕ. In calculating the positions on each line of sight, the direction cosines of the line with respect to the X, Y, and Z axes are determined first, then the intersection of the line of sight and the blocking circle positions are checked to determine if the length of the line of sight needs to be adjusted due to occlusion by one of the circles. Next, increments ΔX, ΔY, and ΔZ corresponding to the input value of Δs are calculated, and the coordinates of the center of the first element on the line of sight is completed ($X = X_p + \Delta X/2$, $Y = Y_p + \Delta Y/2$, and $Z = Z_p + \Delta Z/2$). Coordinates of each subsequent point are computed by successively incrementing the coordinates by ΔX, ΔY, and ΔZ.

As the coordinate of each point is computed, it is tested to determine if it is within the flow field. If it is not, the temperature at that point is set equal to zero and the next point is considered. If it is in the flow field, a modified form of linear interpolation is used to determine the gas properties. The procedure used for axisymmetric flow fields is

illustrated below (subscript w is the point at which any property P is to be computed)

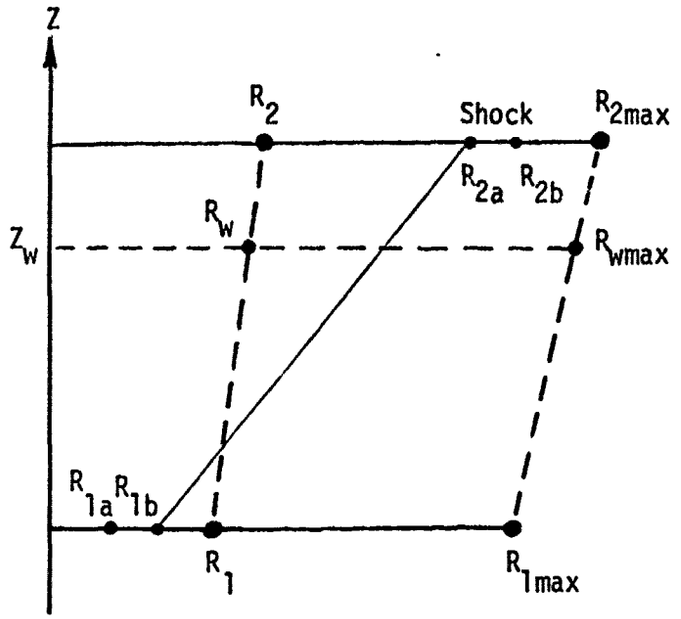
$$ZR = (Z_w - Z_1)/(Z_2 - Z_1)$$

$$R_{wmax} = R_{1max} + ZR(R_{2max} - R_{1max})$$

$$R_1 = R_{1max}(R_w/R_{wmax})$$

$$R_2 = R_{2max}(R_w/R_{wmax}$$

$$P_w = P_1 + ZR(P_2 - P_1)$$



If the shock position is not specified, the properties P_1 and P_2 are those computed at R_1 and R_2 using linear interpolation between the points on either side of R_1 and R_2. If the shock position is specified (see Special Option 10), the interpolation procedure is modified. For the case illustrated in which the shock position is outside the point under consideration, only properties at points inside the shock would be used for interpolation. Therefore, the properties at points R_{1a} and R_{1b} (the last two points inside the shock location) are linearly extrapolated to the radius R_1. This gives

$$P_1 = P_{1a} + (P_{1b} - P_{1a})(R_1 - R_{1a})/(R_{1b} - R_{1a})$$

Similarly, if Rw were just outside the shock, R_1 would be treated normally, but the properties of R_2 would be extrapolated from R_{2a} and R_{2b} (the first

two points following the last point inside the shock).

In the three-dimensional flow field interpolation, the interpolation on R is carried out as described above for the two values of η surrounding the point to be defined. Then an interpolation in the η direction is carried out in the same fashion as that just described for R, so that the interpolated points on each η plane have the same radius ratio relative to the assumed gas boundary. After properties are determined at each point on each line of sight, the radiation calculation is started.

The use of stepwise summations to represent the integrals in the radiation calculations saves computer time and storage and, when carefully handled, is expected to give accuracy consistent with the definition of the gas properties and band model parameters. Caution must be observed in selection of the geometric intervals of integration, so that results represent the variations in gas properties. The increment along the line of sight, Δs, should be chosen so that large changes in transmissivity do not occur in any single increment. Achievement of this goal can be judged to some extent by evaluating the changes in integrated transmissivity along a line of sight (using NLINE = 2 or 3). If the transmissivity changes greatly between integration steps in a region of rapidly changing properties, then a smaller step size should be tried. A temperature criteria (Special Option 19) has been provided to allow the use of a small step size to define regions of rapid change without making unnecessary calculations in regions of relatively constant properties.

An evaluation of the numerical accuracy of the angular integration can be made by comparing the output exact value of the total "shape factor" with the numerical value (where "shape factor" = $\int \sin\theta \cos\theta \, d\theta d\phi$). However,

determining if the angular increments are small enough to define the property variations in the gas has to be a matter of judgement.

FUNCTIONAL STRUCTURE

The program is divided into two overlay subroutines which call additional overlay subroutines. The two major subroutines, FLOW and RAD, separate the functions of interpolation in the gas property data and computation of the radiation, so the flow field property data and the radiation coefficient data do not have to be stored simultaneously. Functional arrangement of the program and the logic used in calling the subroutines is illustrated in Figure 3, and a brief description of the function of each subroutine is given below.

MAIN

This subroutine reads the initial control cards and controls calling the two major subroutines.

FLOW

This controls the subroutines which output the case data and prepare the flow field gas property data for the radiation calculation.

FLOWIN

This subroutine reads the initial identifying portions of the flow field input and the input data necessary for the flow field interpolation, and writes the input data on tape 10. It also identifies the constituents in the flow field and indexes them for later manipulation.

FLOUT

This subroutine reads tape 10 to prepare the initial printed output describing the problem limits and leaves tape 10 in position to read or write the first set of interpolated data along a line of sight.

FLOW2D

This subroutine prepares gas property data along lines of sight by interpolation in an axisymmetric flow field and writes these data on tape 10. When the program returns from this subroutine, the line of sight data on tape 10 is complete for the problem limits specified. This subroutine also provides printed output of the flow field properties and prepares a flow field on tape 8 if IFLOTP>0.

FLOW3D

This subroutine prepares gas property data along lines of sight by interpolation in a three-dimensional flow field and writes these data on tape 10. When the program returns from this subroutine, the line of sight data on tape 10 is complete for the problem limits specified. This subroutine also provides printed output of the flow field properties, and prepares a flow field on tape 8 if IFLOTP>0.

SKIP

The subroutine SKIP renews the output page and line count. It is called from FLOUT only.

RAD

This controls the operation of subroutines for the radiation calculation and output.

ACDATA

This subroutine provides for modification of the absorption coefficient data as required, and provides printed output of the absorption coefficient data used.

MODL3A

This subroutine calculates radiation using the method described as Model 3A. The line of sight data on tape 10 is used as input, and printed output of the spectrally integrated radiation data is provided.

MODEL3

This subroutine calculates radiation using Model 3 equations with the number of line groups n + 1 = IRAD. It uses tape 10 as input and provides printed output of the spectrally integrated radiation results.

SPCOUT

This subroutine provides for printing and plotting output for the spectral distribution of the radiation data.

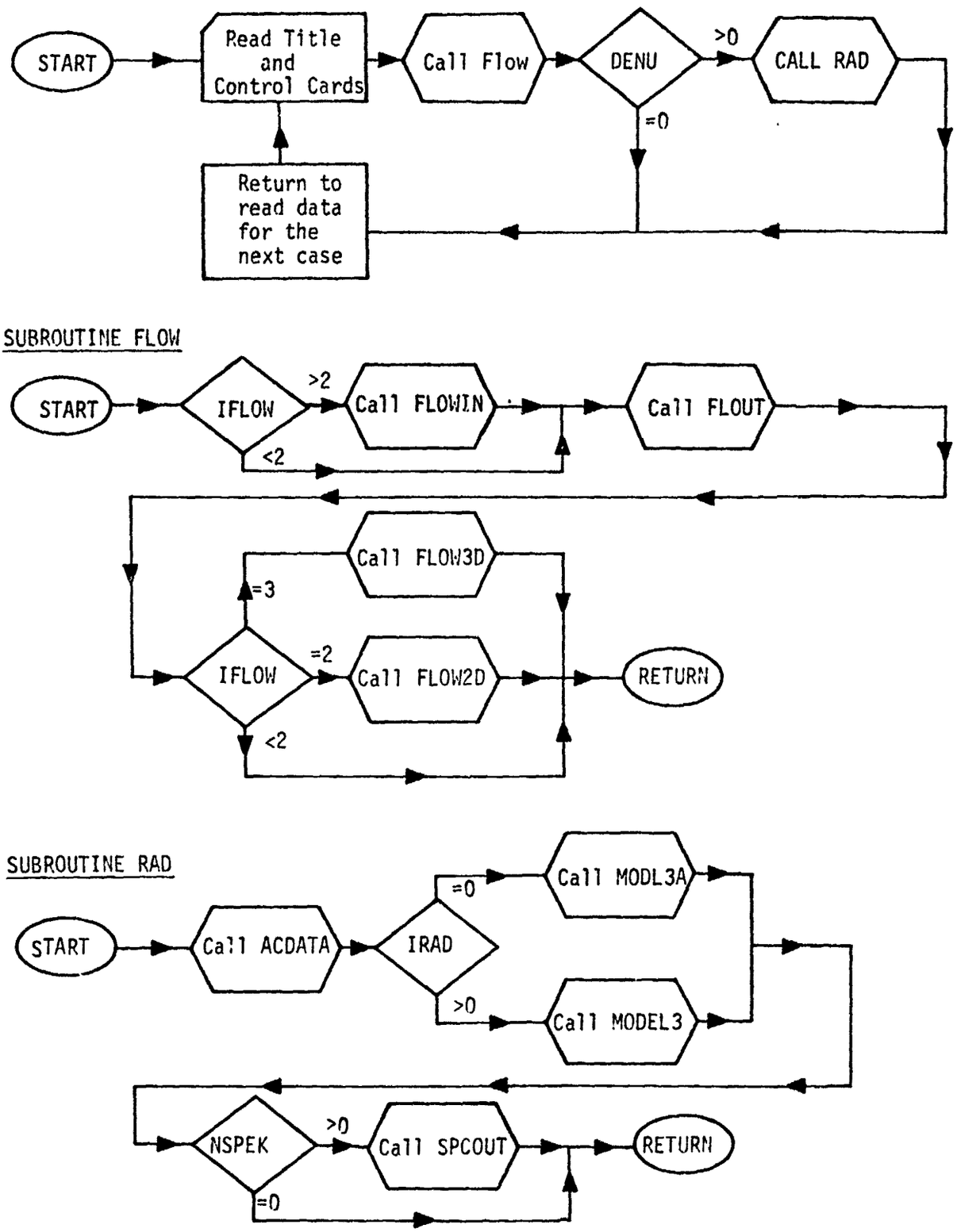


Figure 3. Program Arrangement

INPUT/OUTPUT

The program can be operated with card input and printed output, but options using tapes and providing plotted output are available for convenience. Band model data is included in the program, but the 1/d values for CO_2 must be modified using card input for making calculations with Model 3 (refer to Description of the Problem).

Geometric description of the gas property data can be input using a tape generated by an axisymmetric method-of-characteristics program (Refs. 1 and 2). The radiation program can also generate a flow field tape for later use from either card or tape input with modifications (such as scaling or carbon addition) dictated by the radiation program input.

The tape with the gas property data ordered along each line of sight, which is generated normally as a working tape, can be saved and used as input. This is convenient for restarting an incomplete calculation or for running a problem again with scaled properties or reduced integration limits.

Plotted output is available for the spectral distribution of the integrated radiation and for the transmissivity and optical properties on the last line of sight processed.

Detailed descriptions of the input and output formats are given in Appendix B.

SPECIAL OPTIONS

This program has many special options. They will be briefly described in the order in which they appear in the input data.

1. The gas property data (flow field) may be input from cards or tape. If desired, a previously generated line-of-sight tape may be rerun (IFLOW≤1) with changes in only output form or scaling (KASE = 0). However, if problem limits are to be reduced, KASE must match the case number used when generating on tape 10.
2. An input flow field may be modified by the addition of a specified carbon mole fraction (see Opiton 6) and then output on another tape which may or may not contain additional cases. This allows flow fields to be put on tape from cards, modified and preserved to simplify future runs, or consolidated to reduce the number of tape being used.
3. The radiation calculation may be performed from a line-of-sight tape previously generated, or from either axisymmetric or three-dimensional gas property input data.
4. The plane of the point of interest in the radiation calculation can be defined either by nine direction cosines or by a single angle of inclination. When the angle of inclination (OMEGA) is specified, the Z-axis must be in the U-W plane. OMEGA is the angle measured from the +Z-axis to the +W-axis. With OMEGA equal 0, the positive U axis intersects and is perpendicular to the Z-axis. Positive OMEGA ratation is clockwise about the V-axis when looking in the positive V direction.
5. Up to 50 blocking circles may be used to simulate structure which may block the radiation lines of sight. The blocking circles may be

either "disks" or "holes", and each circle is located by the coordinates of its center and its radius. When a line-of-sight passes through a "disk" or outside a "hole" it is terminated at the blocking circle. The blocking circles are restricted to being parallel to the X-Y plane.

6. Carbon particles (soot) may be added in three ways to flow fields which do not contain them. The carbon mole fraction (treating it as a gas with mole weight of 12.01) may be added as (1) a constant, (2) a function of radial position, or (3) as a function of radial and axial position.
7. The radiation calculation results may be output in any of four forms with varying degrees of detail. These methods are explained in the input instructions.
8. The program is arranged to display several forms of spectral output including plots. See input instructions for further definition.
9. To reduce output bulk, abbreviated forms of both flow field and absorption coefficient output are provided. In the abbreviated form, only the first and the last entry in each block of data is printed to assure proper input operation.
10. In order to define the discontinuity in gas properties caused by a shock wave, an option is provided to input the exact shock position. This allows the flow field interpolation procedure to identify the position of the point being defined relative to the shock wave, so

that the interpolation may be modified when required. The result is a sharp break at the shock position between hot and cold gas rather than a smeared out warm region. This option may use a shock location defined in the flow field (ISHOCK = -1) or input separately (ISHOCK = 1). If this option is to be used there must be at least two radial points on each side of the shock.

11. The program does all calculations in the MKS system of units, but the geometric and gas property data may be input in either the English (inches, R, lbf/ft^2) or the MKS (cm, K, atm) system.
12. The flow field dimensions and properties may be scaled, in order to perform parametric studies or convert dimensions to the proper units. When using previously generated line of sight tape (IFLOW$\leq$1), the scale factors will be multiplied by scale factors used in generating the tape.
13. If it is desired to load less than the entire available input flow field, the position of the initial and final Z-planes may be specified.
14. The radiation calculation may be performed using either Model 3 or Model 3A radiation equations (see technical discussion).
15. The program contains the absorption coefficient data which will normally be required for Model 3A, but provisions are made for modifying this data without changing it permanently if it is necessary for a particular problem. The data contained in this program consists of 1620 entries for constituent, parameter, or wavenumber with 7 temperature values for

each entry. The arrangement is:

Constituent	Parameter	Position in Table	Lower Value of ν	Upper Value of ν	$\Delta\nu$
H_2O	k	1-439	50	11000	25
	1/d	440-878	50	11000	25
CO_2	k	879-1009	500	3750	25
	1/d	1010-1140	500	3750	25
CO	k	1141-1194	1025	2350	25
HCl	k	1195-1284	1000	3225	25
	1/d	1285-1374	1000	3225	25
HF	k	1375-1497	1400	4450	25
	1/d	1498-1620	1400	4450	25

The analytical expression listed for H_2O 1/d in Table 1 can be used rather than the tabulated values by setting ICOEFF =-1. (In normal usage this will not usually be required, and the logic which allows the analytical expression in Model 3 and Model 3A could be removed to save time. On the other hand, if storage becomes a problem, the tabulated values could be eliminated in favor of the analytical expression.) When modifying the tabulated values of k or 1/d (i.e., to input $1/d_o$ used in Model 3 for CO_2 or to change the wavenumber range or interval), two restrictions must be observed:

(a) The total number of entries must not exceed 1620 and the number of temperature values for each entry must not exceed 7.

(b) If both k and 1/d are tabulated for a constituent, the wavenumber range for both parameters must be identical. For example if 1/d is modified for CO_2, the input tabulated data must contain 132 entries starting at ω= 500 with $\Delta\omega$=25. However, if both k

and 1/d are modified, a wavenumber range different from that existing in the program may be used.

16. The absorpiton coefficients may be scaled in order to perform parametric studies or convert dimensions to the proper units $(cm^{-1})_{STP}$.

17. In order to provide more uniform spatial integration, the parameter TANGLE = cos θ sin θ ΔθΔφ may be specified (card 4). The value of TANGLE will be used to compute a value of DPHI to be used for the integration increment at each value of θ. However, if it is smaller than the input DPHI, the input DPHI will be used as the integration increment.

18. A line of sight tape may be prepared by the program without making a radiation calculation by setting DENU = 0.

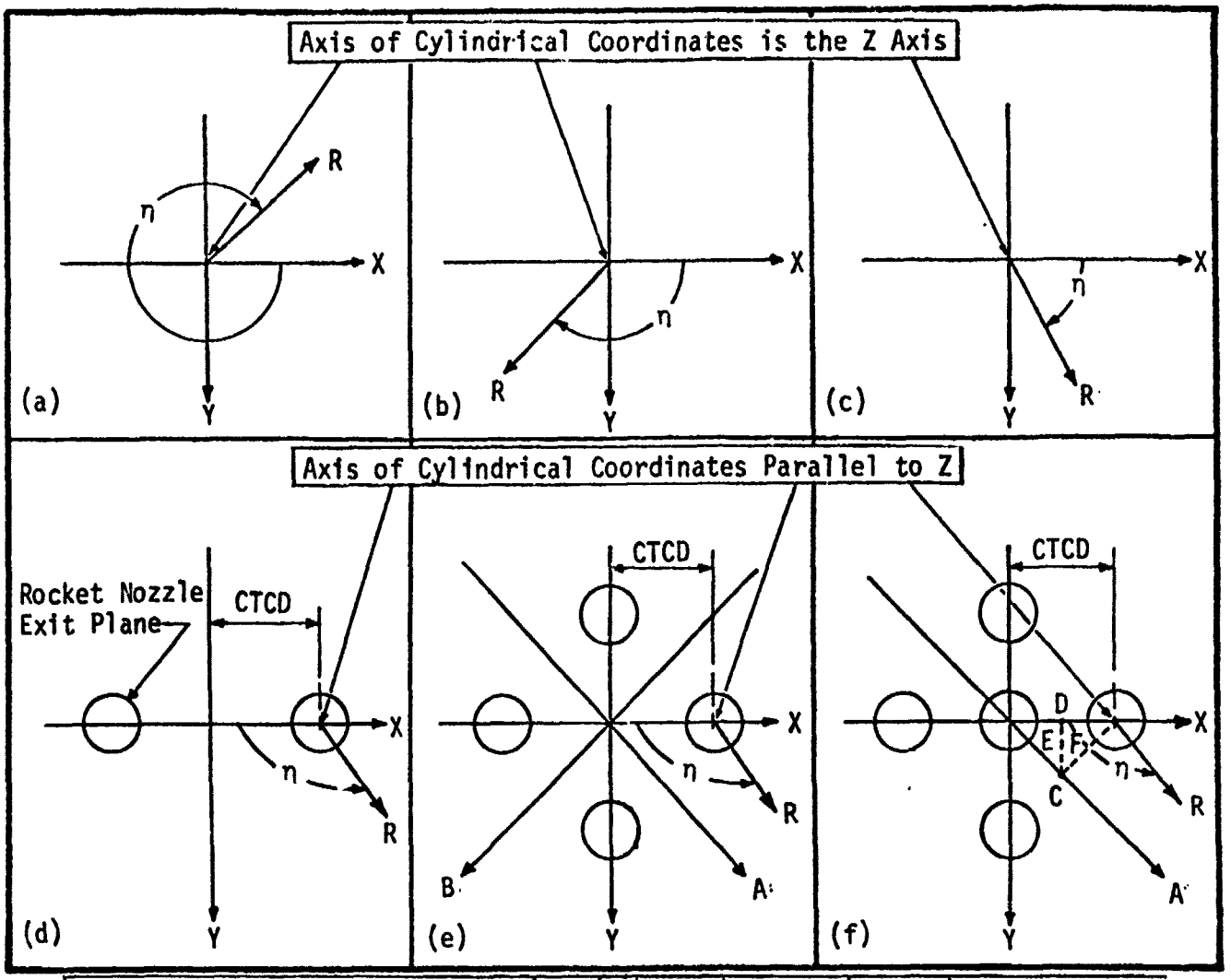
19. A temperature step criteria, TDIFF, is provided to vary the geometric integration step, Δs, depending upon the variations of temperature in the flow field. With TDIFF >0, the flow field is interpolated using steps of Δs and summing the property values until the temperature change from the first point in the integration increment is approximately equal to TDIFF. When this occurs, the property values are averaged and a step in the radiation calculation is computed.

20. An option is provided to exclude insignificant absorption coefficients from the radiation calculation to save time. If an absorption coefficient is less than or equal to ACMIN, it will be neglected.

21. The form of three-dimensional gas property data has been made as flexible as possible to reduce the number of data points by taking advantage of symmetry such as that resulting from a uniform arrangement of multiple rocket engines. The form used is presented to

the program by the value of three input parameters: HANG, CTCD, and ISYMSC. Several typical examples are presented in Fig. 4 to clarify the form of the gas property coordinate system and the use of the three input parameters. In the general case (Fig. 4(a)), the angle about the Z-axis over which property data is provided (HANG) is a full 360 degrees. With symmetry about the XZ plane, HANG is reduced to 180° (Fig. 4(b)), and addition of symmetry about the YZ plane allows a reduction of HANG (and η) to 90 degrees. If it is desired to offset the axis of the cylindrical coordinate system for the gas properties as in Fig. 4 (d) , the offset distance is CTCD. In using this option, the axis of the cylindrical coordinate system must be in the XZ plane parallel to the Z-axis, and η and R must be chosen so that the gas properties are bounded by the XZ and YZ planes. This technique can be extended to smaller symmetric sectors as in Fig. 4(e). For cases in which a center engine is used, it may be desirable (although not technically correct) to assume symmetry about a plane between the center and outboard engine as in Fig. 4(f). In this case ISYMSC is set equal 0, and η and R must be chosen so that the gas properties are bounded by CD as well as the radial planes of symmetry.

In all cases illustrated in Fig. 4, the maximum range of η is irdicated. However, if the gas terminates before the upper limit of η, it is not necessary to carry the flow field description to the upper limit.



Case	ISMSC	CTCD	η	HANG	Comments
(a) General	1	0	0°-360°	360°	
(b) Symmetric about XZ plane	1	0	0°-180°	180°	
(c) Symmetric about XZ and YZ planes	1	0	0°-90°	90°	
(d) Symmetric about XZ and YZ planes and flow field off center	1	>0	0°-180°	90°	R bounded by YZ plane
(e) Symmetric about XZ, YZ, AZ, and BZ planes	1	>0	0°-180°	45°	R bounded by AZ
(f) Symmetric sectors as in (e) plus symmetry of regions E and F about CD	0	>0	0°-180°	45°	R bounded by CD and AZ

Fig. 4. Examples of Techniques for specifying three dimensional flow fields.

RESTRICTIONS AND LIMITATIONS

This program has many liritations caused by storage, but methods have been incorporated which remove some of the limits imposed on previous gaseous radiation programs.

The general limitations on the flow field subroutines are as follows:

Maximum number of constituents to be stored is 6

Maximum number of Z-planes used for the addition of carbon (ICARB>0) is 10

Maximum number of η-values used for the addition of carbon (ICARB>0) per Z-plane is 7

Maximum number of radial points used for the addition of carbon (ICARB>0) is 10

Maximum number of Z-planes at which shock radii may be specified when shock radii are added (ISHOCK = 1) is 20

Maximum number of η-values at each Z-plane for which shock radii may be specified is 13

Maximum number of blocking circles is 50

In addition to these limitations, each flow field interpolation subroutine (FLOW2D and FLOW3D) has specific limitations. In each of these subroutines, the number of Z-planes which may be used is unlimited, since the program is arranged to handle a portion of the flow field at a time.

In FLOW2D, the maximum number of radial points permitted is 100. If the number of points exceeds 100, points will be skipped to reduce the data to less than 100 points. The maximum number of Z-planes which is permitted in storage is 10, but the program will automatically subdivide the flow field so that any number of Z-planes may be used. However, the length of the flow field which can be used is regulated indirectly by a limit of 300 points

along any line of sight. If this limit is exceeded, a diagnostic message is printed, and the calculation is stopped.

In FLOW3D, the maximum number of radial points permitted is 30. If the number of points exceeds 30, points will be skipped to reduce the data to less than 30 points. The maximum number of η-values at any Z-plane is 13. If this number is exceeded, the program will stop and print a diagnostic message. Only 3 Z-planes are permitted in storage at any time, but the program automatically subdivides the flow field so that any number of Z-planes may be used. The maximum number of points permitted along any line of sight is 300. If this limit is exceeded,a diagnostic message is printed, and the program stops. Geometry restrictions are described in Special Option 21.

In the radiation calculation subroutines, the limits on the number of constituents and number of points allowed on a line of sight are compatible with the flow field subroutines. The primary limitations of interest in the radiation subroutines are those pertaining to storage of spectral and constituent radiation data.

Space is provided for a table of coefficients with up to 1620 entries and up to 7 temperature values for each entry. This allows the storage of 1620 items of data specified by constituent or wavenumber, with seven temperature dependent values for each item. The coefficient data may be either absorption coefficient or line density (1/d) data, and the position for the storage of data for each constituent is flexible. The position of the initial coefficient in the table for each constituent is specified to be ICOEF (I) for absorption coefficients of IFIN (I) for line density. The number of temperatures at which data is stored is specified as NACT (I) for

absorption coefficients or NFINT (I) for fine structure parameters. The coefficient data is stored in the block data statements, so the problems associated with the coefficient storage limitations need only arise if this data is modified.

The maximum number of spectral intervals which may be used is 440 ((ENUF-ENUI)/DENU +1 $\leq$ 440). If this limit is exceeded, the program will stop and print a diagnostic message.

The maximum number of combined spectral intervals for all gaseous constituents must not be greater than 840 (NUDIM). If this limit is exceeded in MODL3A, the calculation will stop and a diagnostic message will be written. The limit cannot be exceeded in MODEL3 since the storage is allocated to contain the calculation within the desired dimension. However, an additional limitation is placed on MODEL3 that the number of line groups (IRAD) must not exceed 10. If it does, a diagnostic message is written and the program returns to try to read the next case.

Since a line of sight may be traversed several times for MODEL3 in order to complete the spectral range desired within the NUDIM storage limitation, the spectral output will only be for the spectral range of the last traverse if NSPEK = 2 or 4. In addition, the line of sight output using NLINE = 2 or 3 will be limited to first traverse.

The restrictions on modifying the absorption coefficient data are described in Item 15 of SPECIAL OPTIONS.

RESTART PROCEDURE

The restart procedure will depend upon the type of output desired. For example, if spectral output for the entire problem is desired, the radiation calculation must be completed at one time. However, in the case for which the total irradiance is of primary interest, the program may be restarted. In any case, a few minutes may be saved if tape 10 is saved so that the line of sight property data does not have to be recomputed. Therefore, instructions should be given to save tape 10 if a lengthy problem is being run. If the problem is to be restarted from a previously generated tape 10, IFLOW should be set at 1, and only the first 6 data cards are required.

The irradiance is continually summed throughout the calculation with output depending upon the output option (NLINE) selected. If NLINE = 0, the accumulated irradiance (FLUX) is output at the end of each θ increment, but with all the other NLINE options the accumulated irradiance is output after each line of sight. When the program is restarted, the upper limit of the final value of THETA which is completely finished, should be used as the initial value of THETA (THETAI) when the problem is restarted.

When the restarted run is complete, the irradiance (FLUX) can be added to that predicted by the first run to obtain the total irradiance for the problem.

REFERENCES

1. Smith, S. D.: Description of a Computer Program to Prepare an Axisymmetric Flowfield Tape for the Gaseous Radiation Program. Lockheed Missles and Space Co., Huntsville Research and Engineering Center, LMSC-HREC D225763, March 1972.

2. Smith, S. D. and Ratliff, A. W.: User's Manual-Variable o/f Ratio Method of Characteristics Program for Nozzle and Plume Analysis. Lockheed Missles and Space Co., Huntsville Engineering and Research Center, LMSC-HREC D162220-IV, June 1971.

3. Study on the Spectral Emissivity of Carbon Particles Produced by a Rocket Motor. Final Report on Contract NAS8-11455, General Dynamics Corp., Convair Division, GD/C-DBE 66-006, May 1966.

4. Thomson, J. D.: A Study of Radiative Properties and Composition of the Turbine Exhaust Products in the F-1 engine. Rocketdyne Division of NAA, R-6743, Sept. 1966.

5. Study on Exhaust Plume Radiation Predictions - Interim Progress Report. Contract NAS8-22363, General Dynamics Corp., Convair Division, GDC-DBE-66-001, January 1966.

6. Study on Exhaust Plume Radiation Predictions - Interim Progress Report. Contract NAS8-11363, General Dynamics Corp., Convair Division, GDC-DBE-66-001a, February 1966.

7. Study on Exhaust Plume Radiation Predictions. Final Report on Contract NAS8-11363, General Dynamics Corp., Convair Division, GDC-DBE-66-017, December 1966.

8. Study on Exhaust Plume Radiation Predictions. Progress Report, Contract NAS8-21082, General Dynamics Corp., Convair Division GDC-DBE67-021, November, 1967.

9. Handbook of Infrared Radiation from Gases. NASA SP in preparation by Marshall Space Flight Center.

10. Krakov, B., Babrov, H. J., et. al.: Use of the Curtis-Godson Approximation in Calculations of Radiant Heating by Inhomogenous Hot Gases. NASA TM X-53411, March 15, 1966.

11. Ludwig, C. B.: J. Opt. Soc. of Am., Vol. 10, 1057 (1971).

APPENDIX A

DEFINITION OF TERMS

DEFINITION OF TERMS

MENMONIC	MATH SYMBOL	DEFINITION	UNITS
ABSCL(I)		Absorption coefficient scale factor for constituent I.	
AC	k(STP)	Absorption coefficient at standard temperature and pressure	(1/cm)STP
ACMIN		Minimum absorption coefficient to be considered in radiation calculations. Input on card 6.	(1/cm)STP
ACO(I)		Summation of the collision broadened fine structure parameter (γ_c/d) times ku.	
ADO(I)		Summation of the Doppler broadened fine structure parameter (γ_D/d) times ku.	
AVGG		Average of spectral transmissivities $\left(\sum_{\omega_i}^{\omega_f} \tau(s,\omega)/(\omega_f - \omega_i)\right)$	
BCCO	γ_c	Collision half-width for carbon-monoxide.	1/cm
BCCO2	γ_c	Collision half-width for carbon-dioxide.	1/cm
BCDI	a_c	Collision broadened fine structure term γ_c/d.	
BCDICO	a_c	Collision broadened fine structure term, γ_c/d, for carbon monoxide.	
BCH2O	γ_c	Collision half-width for water vapor.	1/cm
BD	γ_D	Doppler half-width.	1/cm
BDCO		Doppler half-width for carbon-monoxide divided by ω.	
BDCO2		Doppler half-width for carbon-dioxide divided by ω.	
BDH2O		Doppler half-width for water vapor divided by ω.	

MNEMONIC	MATH SYMBOL	DEFINITION	UNITS
BDDI		Doppler broadened fine structure term γ_D/d.	
BETA		Flow field propellant or gas identification.	
COEF(L,K)		Absorption coefficient (k) c · line density (1/d) in the table of coefficients loaded at the temperature index L for table position index K.	
COLT		Collision broadening term in the combined optical depth, Y.	
CRATIO		Radial location of carbon mole fraction as a fraction of the miximum radius. Input on card 14.	
CTCD		Spacing between flow field axis and the Z-axis. Input on card 19.	cm or in.
DASH		Incremental value of Planck's function times the differential of the transmissivity.	watts/cm-sr
DATE		Date of run.	
DENU	$\Delta\omega$	Increment for the spectral summation	1/cm
DFO		Incremental value of the optical depth, D*.	
DIN	1/d	Line density	
DINH2O		Fraction of 1/d used as $1/d_o$ for water vapor.	
DINSCL(I)		Fine structure parameter scale factor for consittuent I.	
DINV	1/d	Line density.	cm
DINVCO	1/d	Line density for carbon monoxide	cm
DOPT		Doppler term in the combined optical depth, Y.	

MNEMONIC	MATH SYMBOL	DEFINITION	UNITS
DMO	X	Sum of the optical depths for all constituents.	
DPHI	$\Delta\phi$	Integration increment for the ϕ integral	deg
DPHIS		Storage for input value of DPHI.	deg
DS		Integration interval along the line of sight	in or cm
DSFACT		Increment of SFACT and TSFACT for a single line of sight. ($\sin\theta \cos\theta \Delta\theta\Delta\phi/\Pi$)	
DSFLUX		Incremental value of the radiation flux for a geometric increment along a line of sight ($N_\omega^\circ \Delta\tau \sin\theta \cos\theta\Delta\theta\Delta\phi\Delta\omega$).	watts/cm^2
DSS	Δs	Geometric integration step along the line of sight. This differs from DS in that it may be a sum of individual geometric values over a temperature increment.	
DTHETA	$\Delta\theta$	Increment for the summation over θ	deg
DUCARB		Incremental value summed to give UCARB.	gm/cm^2
DUCO		Incremental value summed to give UCO.	atm-cm
DUCO2		Incremental value summed to give UCO2.	atm-cm
DUH2O		Incremental values summed to give UH2O.	atm-cm
ELAM		Wavelength	micron
ENU	ω	Wavenumber at the center of a $\Delta\omega$ wavenumber interval.	1/cm
ENUF	ω_f	Upper limit of the ω integral.	1/cm
ENUI	ω_i	Lower limit of the ω integral.	1/cm

MNEMONIC	MATH SYMBOL	DEFINITION	UNITS
EPS	ε	Parameter used for g_n in computing $1/d_n$ for carbon dioxide.	
ETA(I,K)		Value of η in the K-position on the Ith Z-plane.	deg
ETAC(I,K)		Angular position of the Kth carbon value in the Ith Z-plane. Input on card 13.	deg
EXPO(1,N)		Fraction of the water vapor absorption coefficient for the nth line group.	
EXPO(2,N)		Fraction of the carbon dioxide absorption coefficient for the nth line group.	
EXPO(3,N)		Fraction of the carbon monoxide absorption coefficient for the nth line group.	
EYE	$N°_{\omega}$	Plack's function	watts/cm^2-sr
F1SCAL		Scale Factor for the first mole fraction.	
F2SCAL		Scale factor for the second mole fraction.	
F3SCAL		Scale factor for the third mole fraction.	
F4SCAL		Scale factor for the fourth mole fraction.	
F5SCAL		Scale factor for the fifth mole fraction.	
F6SCAL		Scale factor for the sixth mole fraction.	
FC(I,L,K)		Carbon mole fraction. Input on Card 14.	
FF(J,L)		Mole fraction of the Lth constituent being read in from the flow field tape at radial point J.	

MNEMONIC	MATH SYMBOL	DEFINITION	UNITS
FLUFF		Product of integration intervals ($\Delta\theta\Delta\phi\Delta\omega$).	
FLUX	$\dot{q}/A$	Radiant heat transfer rate per unit area. When used as intermediate output, it is the summation of the radiant heat transfer rate up to the point at which it is printed.	watts/cm^2
FO(I)	X*	Optical depth for the weak line approximation at the Ith wavenumber interval.	
FOC(I)	X*	Optical depth for carbon particles at the Ith wavenumber interval.	
FW(L)		Mole fraction of the Lth constituent at the line-of-sight point under consideration. (Index based on input order on card 9).	
FWSUM(II)	s	Sum of mole fractions for the IIth constituent over a temperature increment.	
G1 thru G6	$(\gamma_{i,j})_{STP}$	Collision broadening term for the unidentified gas represented by PREM. Contained in program data statement. Can be modified using card 25.	1/cm-atm
GAM		Ratio of temperature to standard temperature (273K) to the 1/2 power.	
GNEW(I)	$\tau(s,\omega)$	Transmissivity for the position s and the Ith wavenumber interval centered at ω.	
HANG		Flow field sector angle. Input on card 19.	
HDG		Flow field title.	
IBLOCK		Number of blocking circles. Input on card 2.	
ICARB		Carbon option. Input on card 2.	
ICOEF(L)		Position of the first absorption coefficient for the constituent L in the table of coefficients.	

MNEMONIC	MATH SYMBOL	DEFINITIONS	UNITS
ICOEFF		Option to modify absorption coefficient data. Input on card 2.	
IDENTC(I)		Constituent names recognized by the program. The order of IDENTC list in the MAIND deck governs the order of operation of the program.	
IDENU	$\Delta\omega$	Increment for the summation over ω	1/cm
IDNU(I)		Wavenumber interval in the table of coefficients for the Ith constituent.	1/cm
IENUI	ω_i	Lower limit of the ω integration	1/cm
IENUF	ω_f	Upper limit of the ω integration.	1/cm
IFLOTP		Index to control production of a flow field tape. Input on card 2.	
IFLOW		Index to specify manner of flow field input. Input on card 2.	
IMOD		Number of constituents for which coefficient data is to be modified. Input on card 26.	
IPLANE		Option for specification of plane orientation. Input on card 2.	
IRAD		Number of line groups to be used in Model 3 radiation calculation. Input on card 2.	
ISCALA		Absorption coefficient scaling option. Input on card 2.	
ISCALF		Geometry and gas property scaling option. Input on card 2.	
ISHOCK		Shock plane option. Input on card 2.	
ISYMSC		Three dimensional flow field parameter. Input on card 19.	
INUITS		Input units option. Input on card 2.	

MNEMONIC	MATH SYMBOL	DEFINITION	UNITS
IZF		Index of final Z-plane to be considered in an input flow field. Input on card 2.	
IZI		Index of initial Z-plane to be considered in the input flow field. Input on card 2.	
IZSH		Index of the initial Z-plane in the flow field for which shock data is specified. Input on card 15.	
IZSUM		Index of the most recently loaded (input) Z plane referenced to the complete gas flow field.	
JPLOT(I)		Plotting control input on card 32.	
JFK		Index used to indicate the number of geometric steps within a temperature step interval.	
KASE		Case number. Input on card 2.	
KCARB		Index of the carbon mole fraction in the flow field storage when ICARB>0.	
KIND(I)		Indicates if the Ith blocking circle is a disk (0) or a hole (1).	
KON(I)		Constituent name. Each name consists of two A6 words, but none of the names use more than 7 characters. The name cannot be changed unless the program used to generate the flow field input tapes is modified. Input on card 9.	
LBLOCK		Index to indicate if the line of sight has been blocked by a blocking circle. If it has been blocked, LBLOCK will be the index of the blocking circle which blocked it.	
LIBCON		Number of constituents identified in the program.	

MNEMONIC	MATH SYMBOL	DEFINITION	UNITS
LOSPT		Index for the position of points along a line of sight.	
LOSFLX		Summation of the heat flux per unit area along a line of sight ($\Sigma N^{\circ}_{\omega}\Delta\tau \sin\theta \cos\theta \Delta\theta\Delta\phi \Delta\omega$)	watts/cm^2
LPT		Number of line of sight points on a tape record.	
LSET		This index provides the number order for the lines of sight on the line of sight tape. A zero value indicates the end of all line of sight records on the tape, and a negative value indicates that the line of sight has either been blocked or missed the flow field.	
NABS		Absorption coefficient output option. Input on card 2.	
NACT(I)		Number of temperature values at which absorption coefficients are stored for the Ith constituent.	
NET		Number of η values in a Z-plane.	
NETA(I)		Number of η values in the Ith Z-plane.	
NETAS		Number of η values in a Z-plane.	
NFINT(I)		Number of temperature values at which fine structure parameters are stored for the Ith constituent.	
NFLOW		Flow field output option. Input on card 2.	
NLINE		Radiation output option index. Input on card 2.	
NOCON		Number of constituents stored on flow field input tape.	
NOETAS(I)		Number of η values input at the Ith Z-plane for shock data. Input on card 15.	

MNEMONIC	MATH SYMBOL	DEFINITION	UNITS
NOETAC(I)		Number of η values used for loading carbon mole fraction at the Ith carbon Z-plane. Input on card 12.	
NOKON		Number of constituents to be considered for the radiation calculation. Input on card 2.	
NOPS		Number of points on a radial line in the flow field.	
NOPSFC(I,L)		Number of points at which carbon mole fraction is specified at the Ith carbon Z-plane and Lth η position. Input on card 13.	
NPLOT		Number of plots desired. Input on card 2.	
NR(I)		Number of radial points at ZZ(I).	
NR(I,J)		Number of radial points at ETA(I,J).	
NSPEK		Spectral output option. Input on card 2.	
NU	ω	Wavenumber at the center of a $\Delta\omega$ wavenumber interval.	1/cm
NUDIM		Number of storage positions reserved for optical depth parameters of gaseous radiators.	
NUF	ω	Upper limit of the ω integral.	1/cm
NUI	ω	Lower limit of the ω integral.	1/cm
NUL(I)		Value of the minimum wavenumber in the table of the absorption coefficients for constituent I.	
NUMBER(I)		Position of the constituent in the IDENTC list for which the coefficient data is to be modified. Input on card 26.	

MNEMONIC	MATH SYMBOL	DEFINITION	UNITS
NUMCON(I)		Index of the position of the Ith constituents in the identifying data list (IDENTC) in the program.	
NUU(I)		Value of the maximum wavenumber in the absorption coefficient table for constituent I.	
NFZS		Index of the last Z-plane in the flow field for which shock data is specified.	
NZFC		Number of Z-planes used for adding carbon mole fraction. Input on card 11.	
NZSH		Number of Z-planes for which shock data is loaded. Input on card 15.	
OD(I)	X	Optical depth for the index I. The I index used in the spectral summation is a function of both wavenumber and constituent.	
OMEGA	Ω	Inclination angle of the plane of interest.	deg
P(I,L)	p	Pressure at the Lth point on ZZ(I).	psfa or atm
P(I,K,J)	p	Pressure at the Jth point on ETA(I,K).	psfa or atm
PC		Carbon partial pressure corrected for temperature. (Note that carbon particles are trested as a gas of molecular weight 12.011)	atm
PCO	p_i	Carbon monoxide partial pressure corrected for temperature.	atm
PCO2	p_i	Carbon dioxide partial pressure corrected for temperature.	atm
PCORR		Pressure corrected to standard temperature. This is actually a ratio of the gas density to the density at standard conditions.	atm
PH2	p_i	Hydrogen partial pressure corrected for temperature.	atm

MNEMONIC	MATH SYMBOL	DEFINITIONS	UNITS
PH2O	p_i	Water vapor partial pressure corrected for temperature	atm
PHI	ϕ	Angle between the positive V axis and projection of a line of sight in the UV plane.	deg
PHIF	ϕ_f	Upper limit of the ϕ summation.	deg
PHIFS		Storage for input value of PHIF.	deg
PHII	ϕ_i	Lower limit of the ϕ summation.	deg
PHIIS		Storage for input value of PHII.	deg
PN2	p_i	Nitrogen partial pressure corrected for temperature.	atm
PO2	p_i	Oxygen partial pressure corrected for temperature.	atm
PREM		Partial pressure of all remaining gases not accounted for by the identified constituents.	atm
PSCAL		Pressure scale factor.	
PSFINV		Inverse of the integral of $\sin\theta \cos\theta \, d\theta \, d\phi$.	
PW	p	Pressure at the line of sight point under consideration.	atm
PWSUM		Sum of the pressures over a temperature increment.	atm
R(I,L)		Radius of the Lth point on ZZ(I).	in/cm
R(I,K,J)		Radius of the Jth point on ETA(I,K).	in/cm
RADAVG		Average radiance over all lines of sight. (FLUX/(TSFACT*π))	watts/cm^2-sr
RADLOS		Radiance for a particular line of sight. (SUM * $\Delta\omega$)	watts/cm^2-sr

MNEMONIC	MATH SYMBOL	DEFINITION	UNITS
RADPLM		Average radiance of the lines of sight which went through the gas flow field. (FLUX/(SFACT*π))	watts/cm^2-sr
RAM		Ratio of standard temperature (273K) to the gas temperature to the 1/2 power.	
RC(I)		Radius of the Ith blocking circle.	in or cm
RHOC	ρ	Carbon particle density.	gm/cm^3
RSCAL		Geometric scale factor for problem dimensions.	
RSHOCK (I,J)		Shock radial position. Input on card 16.	cm or in
S	s	Distance along a line of sight from the point of interest.	cm
SANKA		Product of the angle factors and integration intervals ($\sin\theta \cos\theta \Delta\theta\Delta\phi\Delta\omega$).	
SFACT		Summation of $\cos\theta \sin\theta \Delta\theta \Delta\phi / \pi$ for the lines of sight which intersect the exhaust plume.	
SFLXTH(I)		Spectral flux in the Ith wave number increment for the current value of θ.	watts/cm^2-cm^{-1}
SFLXTO(I)		Sum of the spectral flux in the Ith wavenumber increment. Also used as storage for spectral output.	watts/cm^2-cm^{-1}
SINKO		The product of $\cos\theta \sin\theta$.	
SMAX	L	Input value of the upper limit of the s summation. Input on card 6.	in or cm
SMIN	L	Value of the upper limit of the s summation after the line of sight has been checked for obstruction.	cm

MNEMONIC	MATH SYMBOL	DEFINITION	UNITS
SUM		Summation over a line of sight of the product of the Planck function ($N°_\omega$) and the differential transmissivity ($\Delta\tau$).	watts/cm^2-s
SUMOLD		Storage location for the radiation flux thru the previous line of sight step.	
SZERO		Lower limit of the summation over s. In this program, it is set at zero.	
T(I,L)	T	Temperature of the Lth point on ZZ(I).	R or K
T(I,K,J)	T	Temperature of the Jth point on ETA(I,K).	R or K
TANGLE		Input value of ($\sin\theta\cos\theta\ \Delta\theta\Delta\phi$) to be used in computing DPHI.	sr
TDIFF		Temperature change limit used in determining integration interval along a line of sight. Input on card 6.	K or R
TEMAC(I,K)		K values of temperatures at which absorption coefficients for the constituent I are listed in the coefficient table.	K
TEMFIN(I,J)		J values of temperature at which line density (1/d) for a constituent I are listed in the coefficient table.	K
THETA	θ	Angle between the surface normal at the point of interest and a line of sight ray from the point of interest.	deg
THETAI	θ_i	Lower limit of the θ summation	deg
THETAF	θ_f	Upper limit of the θ summation	deg

MNEMONIC	MATH SYMBOL	DEFINITION	UNITS
TINDEX		Index used for temperature step computation to determine the type of steps being considered: minus one indicates the initial step on the line of sight; zero indicates the initial step in a new temperature increment; and one indicates a step within a temperature increment that is being summed.	
TSCAL		Temperature scale factor.	
TSFACT		Summation of $\cos\theta \sin\theta \Delta\theta \Delta\phi / \pi$ for all lines of sight.	
TRUESF		Exact value for the integral for $\sin\theta \cos\theta \, d\theta \, d\phi/\pi$ for all lines of sight.	
TWSTO		Temperature at the initial geometric step on a temperature step.	K
TWSUM		Sum of temperatures over a temperature increment.	K
TW	T	Temperature at the line of sight point under consideration.	K
UCARB	u	Density-path length product for carbon particles.	gm/sq-cm
UCO	u	Pressure-path length product for carbon monoxide.	(cm-STP)
UCO2	u	Pressure-path length product for carbon dioxide.	(cm-STP)
UH2O	u	Pressure-path length product for water vapor.	(cm-STP)
ULX		Direction cosine of U-axis with respect to X-axis.	
ULY		Direction cosine of U-axis with respect to Y-axis.	
ULZ		Direction cosine of U-axis with respect to Z-axis.	
VLX		Direction cosine of V-axis with resp ct to X-axis.	
VLY		Direction cosine of V-axis with respect to Y-axis.	

MNEMONIC	MATH SYMBOL	DEFINITIONS	UNITS
VLZ		Direction cosine of the V-axis with respect to the Z-axis.	
WLX		Direction cosine of the W-axis with respect to the X-axis.	
WLY		Direction cosine of the W-axis with respect to the Z-axis.	
WLZ		Direction cosine of the W-axis with respect to the Z-axis.	
X	X	X coordinate at the line of sight point under consideration.	cm
XC(I)		X coordinate of the Ith blocking circle.	in or cm
XP		X coordinate of the point of interest.	in or cm
Y	Y	Y coordinate at the line of sight point under consideration.	cm
YC(I)		Y coordinate of the Ith blocking circle.	in or cm
YP		Y coordinate of the point of interest.	in or cm
Z	Z	Z coordinate at the line of sight	cm
ZC(I)		Z coordinate of the Ith blocking circle.	in or cm
ZP		Z coordinate of the point of interest.	in or cm
ZZ(I)		Z coordinate of the Ith Z plane.	in or cm
ZZFC(I)		Z coordinate of the Ith carbon Z plane. Input on card 12.	in or cm

APPENDIX B

INPUT/OUTPUT FORMATS

INPUT CARDS
INPUT/OUTPUT TAPES
PRINTED OUTPUT
DIAGNOSTICS

INPUT CARDS

Card	Format	Col	Computer Name	Value	Description
1	8A10	1-80	TITLE		Problem identification
2	I6,20I3	1-6	KASE	<0	Flowfield input from cards
				0	See Note B on page 59 .
				>0	Case number of flow field on tape 8 If IFLOTP >0 use tape 11
		8	IFLOTP	0	Flowfield not modified
					Flowfield to be modified as required and output on tape if IFLOTP>0
				1	First case on tape 8
				2	Other than first case on tape 8
		9	IFLOW	≤1	Use previous LOS tape mounted on tape 10. See notes on following page.
				2	Axisymmetric flow field input.
				3	3-Dimensional flow field input.
		12	NOKON		Number of constituents to be stored in flow field (maximum of 6).
		15	IPLANE	0	Read OMEGA for plane of inclination.
				1	Read direction cosines of U, V, W, axes.
		17,18	IBLOCK		Number of blocking circles used (50 maximum).
		21	ICARB	0	Read carbon mole fraction from the flow field input (if carbon is called for and available in flow field).
				1	Use constant carbon mole fraction FC=constant
				2	Use carbon mole fraction as a function of radius: FC=f(R) for axisymmetric flowfields and FC=f (η,R) for 3-D flowfields.
				3	Use carbon mole fraction as a function of Z and R: FC=f(Z,R) for axisymmetric flow fields and FC=f (Z,η,R) for 3-D flow fields.

INPUT CARDS (Continued)

Card	Format	Col	Computer Name	Value	Description
2 (cont.)		24	NLINE	0	Output cumulative flux and shape factor at each θ increment.
				1	Output cumulative flux, shape factor, LOS flux, and LOS intensity for each LOS.
				2	Same as 1 plus properties at each radiation step.
				3	Same as 2 plus properties at each geometric step.
		26	NSPEK	0	Spectral output per unit wavelength
				1	Spectral output per unit wavenumber
		27		0	No spectral output desired
				1	Spectral radiance per steradian - short form
				2	Spectral radiance per steradian - long form
				3	Spectral radiance - short form
				4	Spectral radiance - long form
		29,30	NPLOT		Number of plots desired.
		33	NFLOW	0	Short form of flow field output with only first and last radius points.
				1	Complete flow field output.
		36	NABS	0	Short form of absorption coefficient output with only first and last values.
				1	Complete absorption coefficient output.
		39	ISHOCK	-1	Shock location input with the flowfield.
				0	Shock plane not specified.
				1	Shock plane data input.
		42	IUNITS	0	English units (inches, °R, lbf/ft^2) used in all input and output data except absorption coefficients.
				1	MKS units used in all input and output data (cm, °K, atm).

INPUT CARDS (Continued)

Card	Format	Col	Computer Name	Value	Description
2 (cont.)		45	ISCALF	0	No flow field scale factors used.
				1	Flow field scale factors input.
		47,48	IZI	0	Read first Z-plane in the flow field.
				> 0	Index of first Z-plane to be read.
		50,51	IZF	0	Read to end of flow field.
				> 0	Index of last Z-plane to be read.
		53,54	IRAD	0	Use Model 3A radiation calculation
				> 1	Use Model 3 radiation calculation with line groups n = IRAD (maximum of 10)
		57	ICOEFF	0	Use absorption coefficient data in program.
				1	Input modified absorption coefficient data.
				-1	Use analytical expression for H_2O l/d.
		60	ISCALA	0	No absorption coefficient scale factors used
				1	Absorption coefficient scale factors input.

NOTE:

Procedure for using Previously Generated Tape 10

A. If a change is desired in problem limits:
   1. KASE must match the absolute value of the case number used in generating tape 10.
   2. Cards 3-6 are used to specify new limits. (Increments must be the same) The values used must produce line-of-sight angles which exist on the tape.
   3. Omit cards 7-16 and 18-22. Remaining cards are used as required by options chosen.

B. If no change is desired in problem limits:
   1. Set KASE = 0.
   2. Omit cards 3-16 and 18-22. Remaining cards are used as required by options chosen.

INPUT CARDS (Continued)

Card	Format	Col	Computer Name	Units	Description
3	3E10.6	1-10	THETAI	Deg	Initial value = θ_i
		11-20	THETAF	Deg	Final Value = θ_f
		21-30	DTHETA	Deg	Increment = $\Delta\theta$
4	3E10.6	1-10	PHII	Deg	Initial value = ϕ_i Note: ϕ is clockwise from U when viewed in the positive W direction.
		11-20	PHIF	Deg	Final value = ϕ_f
		21-30	DPHI	Deg	Increment = $\Delta\phi$
		31-40	TANGLE	Sr	If this value is specified, $\Delta\phi$ will be adjusted so that $\cos\theta \sin\theta\Delta\theta\Delta\phi$ = TANGLE.
5	3E10.6	1-10	ENUI	cm^{-1}	Wavenumber lower limit, ω_i
		11-20	ENUF	cm^{-1}	Wavenumber upper limit, ω_f
		21-30	DENU	cm^{-1}	Increment, $\Delta\omega$. Must be an interger multiple of the increment in the absorption coefficient table.
6	3E10.6	1-10	TDIFF	R or K	Temperature step size for integration on S.
		11-20	SMAX	in or cm	Upper limit on LOS distance, L.
		21-30	ACMIN	$(cm^{-1})_{STP}$	Minimum absorption coefficient to be used in radiation calculation.
7	6E10.6	1-10	XP	in or cm	X }
		11-20	YP	in or cm	Y } Coordinates of the point of interest.
		21-30	ZP	in or cm	Z }
		31-40	DS	in or cm	Geometric increment along LOS, Δs.

NOTE: If IPLANE = 0, read 8, but if IPLANE = 1, read 8A

8	E10.6	1-10	OMEGA	Deg	Inclination of the plane of interest, Ω
8A	9E8.4	1-8	ULX		Direction cosines for U-X axes.
		9-16	ULY		U-Y
		17-24	ULZ		U-Z
		25-32	VLX		V-X
		33-40	VLY		V-Y
		41-48	VLZ		V-Z
		29-56	WLX		W-X
		57-64	WLY		W-Y
		65-72	WLZ		Direction cosines for W-Z axes.
9	12A6	1-12	KON(1,2)		First constituent
		13-24	KON(3,4)		Second constituent
		25-36	KON(5,6)		Third constituent
		37-48	KON(7,6)		Fourth constituent
		49-60	KON(9,10)		Fifth constituent
		61-72q	KON(11,12)		Sixth constituent

Note: The constituent names must be left justified and must be in the following forms: H2O1(G), ClO2(G),ClO1(G),Cl(S), N2(G), H2(G), O2(G), HCL, HF.

INPUT CARDS (Continued)

Card	Format	Col	Computer Name	Units	Description
USE CARD(S) 10 IF IBLOCK>0. I = 1, IBLOCK					
10	4E10.6, I5	1-10	XC(I)	in or cm	X } Coordinates of the center of the
		11-20	YC(I)	in or cm	Y } blocking circle
		21-30	ZC(I)	in or cm	Z }
		31-40	RC(I)	in or cm	Blocking circle radius
		45	KIND(I)		Type of blockage: 0 = disk; 1 = hole

USE CARDS 11 THRU 14 FOR ADDING CARBON MOLE FRACTION IF ICARB >0.

The order of using these cards is as follows:

IFLOW	ICARB	Procedure
2 or 3	1	Read card 14 one time for FC (1, 1, 1)
2	2	Read card 13 one time for NOPSFC (1, 1) Read card(s) 14,K = 1, NOPSFC (1, 1)
	3	Read card 11 for NZFC Read cards 12 thru 14 for I = 1, NZFC and L = 1
3	2	Read card 12 for NOETAC (1) Read card 13 and 14 for I = 1 and L = 1, NOETAC (1)
	3	Read card 11 for NZFC Read cards 12 thru 14 for I = 1, NZFC Read cards 13 and 14 for I = 1, NZFC and L = 1, NOETAC (I)

Card	Format	Col	Computer Name	Units	Description
11	I2	1,2	NZFC		Number of Z-planes at which carbon mole fraction is input (maximum of 10)
12	I2,E18.0	1,2	NOETAC(I)		Number of η-planes with carbon data at this Z-plane (maximum of 7). Not required for IFLOW = 2.
		3-20	ZZFC(I)	in or cm	Z coordinate of this Z-plane
13	I2,E18.0	1,2	NOPSFC(I,L)		Number of radius points at which the carbon mole fraction is specified.
		3-20	ETAC(I,L)	Deg	Angle of this η-plane (not required for IFLOW = 2)

INPUT CARDS (Continued)

Card	Format	Col	Computer Name	Units	Description
14	8E10.6	1-10	FC(I,L,1)		Carbon mole fraction at radius point 1.
		11-20	CRATIO(I,L,1)		Radius ratio (R/RMAX) at radius point 1.
		21-30	FC(I,L,2)		
		31-40	CRATIO(I,L,2)		
		41-50			
		51-60			
		61-70	FC(I,L,K)		Repeat with as many cards as necessary
		71-80	CRATIO(I,L,K)		up to a maximum of K=10.
USE CARDS 15 AND 16 ONLY IF ISHOCK = 1					
15	22I3	1-3	NZSH		Number of consecutive Z-planes with shock points (maximum of 20)
		4-6	IZSH		Index of first Z-plane for which a shock is specified
		7-9	NOETAS(I)		For IFLOW = 3, this specifies the number of η-planes at which shock points are specified. This should correspond to the η-planes in the flow field at the corresponding Z-plane.
		64-66	NOETAS(NZSH)		
16	8E10.6	1-10	RSHOCK(1,1)	in or cm	Shock radii- list for reading in a double loop going thru J = 1, NOETAS(I) first (inside) and I = 1, NZSH second (outside). For IFLOW = 2, J = 1 only. If no shock exists at a particular value of η, use RSHOCK = 0.
		11-20			
		71-80	RSHOCK(I,J)		
USE CARD 17 ONLY IF ISCALF = 1					
17	9E8.5	1-8	RSCAL		Dimension scale factor
		9-16	TSCAL		Temperature scale factor
		17-24	PSCAL		Pressure scale factor
		25-32	F1SCAL		Mole fraction scale for constituent 1
		33-40	F2SCAL		2
		41-48	F3SCAL		3
		49-56	F4SCAL		4
		57-64	F5SCAL		5
		65-72	F6SCAL		6
USE CARDS 18 THRU 22 ONLY IF KASE <0 (FLOW FIELD INPUT ON CARDS)					
18	72H	1-72	HDG		Flow field description
19	24H,I1, 5X,2E10.6	1-24	BETA		Flow field gas identification

INPUT CARDS (Continued)

Card	Format	Col	Computer Name	Units	Description
		25	ISYMSC	0	Flow field of center engine assumed to be symmetric with that of the outboard engine about a plane which bisects, and is normal to, a plane connecting the engine centerlines. See Special Option 21.
				1	No special assumptions about the center engine flow field or no center engine.
		31-40	HANG	Deg	Included angle of flow field sector, ψ.
		41-50	CTCD	in or cm	Distance from flow field axis to Z-axis. For a symmetrical engine arrangement, the Z-axis must be at the center of symmetry.

Repeat cards 20 thru 22 as required. END FLOW FIELD BY A BLANK CARD.

20	E10.6 I10,I5	1-10	ZZ(I)	in or cm	Coordinate of this Z-plane.
		18,20	NR(I)		IFLOW = 2 only. Number of radius points
			NETA(I)		IFLOW = 3 only. Number of η-planes
		23,25	LS(I)		Used for IFLOW = 2 and ISHOCK =-1 only. Index of the radial point just inside of a shock position. In order for this option to allow the shock location to be recognized, LS(I)$\geq$2, and there must be two points on the outside of the shock.

USE CARD 21 FOR IFLOW = 3 ONLY
Repeat cards 21 and 22 for J = 1, NOETA(I)

21	E10.6 I10,I5	1-10	ETA(I,J)	Deg	Angle of the J th η-plane. J= 1, NOETA(I)
		18-20	NR(I,J)		Number of radius points
		23-25	LS(I,J)		ISHOCK = -1 only. Index (L) of radial point just inside the shock surface. In order this option to perform properly, there must be at least two radial points on each side of the shock.

Repeat card 22 L = 1, NR(I,J)

INPUT CARDS (Continued)

Card	Format	Col	Computer Name	Units	Description
22	9E8.5	1-8	R(I,J,L)	in or cm	Radius (J=1 for IFLOW=2)
		9-16	T(I,J,L)	R or K	Temperature
		17-24	P(I,J,L)	psfa or atm	Pressure
		25-32	F1(I,J,L)	-	First
		33-40	F2(I,J,L)	-	Second
		41-48	F3(I,J,L)	-	Third
		49-56	F4(I,J,L)	-	Fourth
		57-64	F5(I,J,L)	-	Fifth
		65-72	F6(I,J,L)	-	Sixth

Constituent mole fractions - the order must match the order used on card 9 for the constituent names.

23 Blank Card to end the flow field

USE CARD 24 ONLY IF ISCALA = 1

Card	Format	Col		
24	12E6.3	1-6	ABSCL(1)	Absorption coeff. scale factors. The number order is the same as the order in the IDENTC list.
		7-12	ABSCL(2)	
		13-18	ABSCL(3)	
		19-24	ABSCL(4)	
		25-30	ABSCL(5)	
		31-36	ABSCL(6)	
		37-42	DINSC(1)	Fine structure parameter scale factors
		43-48	DINCC(2)	
		49-54	DINSC(3)	
		55-60	DINSC(4)	
		61-66	DINSC(5)	
		67-72	DINSC(6)	

USE CARDS 25 THRU 31 ONLY IF ICOEFF = 1 (Absorption coefficient to be modified)

Card	Format	Col		
25	8F10.6	1-10	G1	Broadening parameter to be used for unidentified gases in the flow field. Number order is the same as the order in the IDENTC list. For example, the unidentified foreign gas broadening parameter for CO_2 is G2.
		11-20	G2	
		21-30	G3	
		31-40	G4	
		41-50	G5	
		51-60	G6	
26	7I5	5	IMOD	Number of constituents for which absorption coefficients will be modified. (If only G values on Card 25 are to be changed, this should be zeros).
		10	NUMBER(1)	NUMBER is the position of the constituent to be modified in the IDENTC list. For example, for CO_2 NUMBER (IMOD) = 2.
		15	↑	
		20	|	
		25	|	
		30	|	
		35	NUMBER(IMOD)	

INPUT CARDS (Continued)

Card	Format	Col	Computer Name	Units	Description
Use IMOD sets of cards 27 thru 31. The sets should be put in the same sequence as used in the NUMBER sequence on card 26.					
27	8I5	1-5	NUL(I)		Initial wavenumber in the table.
		6-10	NUU(I)		Final wavenumber in the table.
		11-15	IDNU(I)		Wavenumber increment in the table.
		20	ICO		0 absorption coefficients will not be modified. 1 absorption coefficients will be modified.
		25	IFI		0 fine structure parameters will not be modified. 1 fine structure parameters will be modified.
USE CARDS 28 AND 29 ONLY IF ICO>0					
28	I5,5X	5	NACT(I)		Number of temperatures in table (7 max)
	7E10.6	11-20	TEMAC(I,K)	K	Temperatures in the absorption coefficient table in order from lowest to highest. K = 1, NACT(I).
		21-30	↑		
		31-40			
		41-50			
		51-60			
		61-70	↓		
		71-80	TEMAC(I,K)		
Number of cards 29 is (NUU(I) - NUL(I))/IDNU(I) + 1					
29	8E10.6	1-10	ENUK(L)	cm^{-1}	Wavenumber for these absorption coefficients
		11-20	COEF(K,L)	$(cm^{-1})_{STP}$	Absorption coefficients for each temperature in the table (K = 1, NACT(I)).
		21-30	↑		
		31-40			
		41-50			
		51-60			
		61-70	↓		
		71-80	COEF(K,L)		
Use cards 30 and 31 only if IFI > 0					
30	I5,5X	5	NFINT(I)		Number of temperatures in table (7 max).
	7E10.6	11-20	TEMFIN(I,K)	K	Temperatures in the table of line densities in order from lowest to highest, K = 1, NFINT(I)
		21-30	↑		
		31-40			
		41-50			
		51-60			
		61-70	↓		
		71-80	TEMFIN(I,K)		

INPUT CARDS (Concluded)

Card	Format	Col	Computer Name	Units	Description
Number of cards 31 is (NUU(I) - NUL(I))/IDNU(I) +1					
31	8E10.6	1-10	ENUK(L)	cm^{-1}	Wavenumber for these line density parameters. Line density (1/d) for each of the temperatures, K = 1, NFINT(I)
		11-20	COEF(1,L)	cm	
		21-30	▲		
		31-40	|		
		41-50	|		
		51-60	|		
		61-70	|		
		71-80	COEF(K,L)		
USE CARD 32 ONLY IF IPLOT > 0					
32	16I5	3-5	JPLOT(I)		A series of NPLOT three digit numbers will be used to give plotting instructions. The first digit will specify the units of the abscissa: 1 = wavenumber - 1/cm; 2 = wavelength - microns. The remaining two digits will specify the variable on the ordinate as follows:
		8-10	I=1,NPLOT		
		▼			
		78-80			
		3-5			
		▼			
		etc.			

Digits	Variable Name	Description
10		Spectral irradiance in watts/cm^2-μ-sr (NSPEK=1 or 2) " "watts/cm^2-μ (NSPEK=3 or 4) " "watts/cm^2-sr-cm^{-1} (NSPEK = 11 or 12 " "watts/cm^2-cm^{-1} (NSPEK=13 or 14)
20	G	Transmissivity
31 thru 37	FO	Optical depth for the weak line limit,X*. Last digit indicates constituent according to IDENTC list.
41 thru 46	ACO	Collision broadened fine structure parameter, parameter, $\bar{a}_c$. Last digit indicates constituent.
51 thru 56	ADO	Doppler broadended fine structure parameter $\bar{a}_D$. Last digit indicates constituent.

INPUT/OUTPUT TAPES

The use of tapes by the program depends upon the options selected. It can operate without input or output tapes, or it can prepare output tapes which may later be used as input. Each tape will be described as its primary function with notes to explain the optional use.

Flow Field Tape

This tape is used when KASE is positive and IFLOW is 2 or 3. It provides input gas property data. The Lockheed developed programs (Refs. 1 and 2) can prepare an axisymmetric flow field tape, but no method is presently available for automated preparation of a three-dimensional flow field tape. Any flow field input on cards or tape can be transferred to a tape using the IFLOTP option.

Density - 800 BPI FORTRAN IV Binary

For IFLOTP = 0: input on Logical 8

For IFLOTP>0: input on Logical 11 (If KASE >0)

output on Logical 8

The composition of the input tape varies slightly depending upon whether the flow field is axisymmetric or three-dimensional. Therefore, the tapes will be described separately. Several flow field cases may be stacked on one tape. The last case on a tape is followed by an end of file,or a record in which each of the twelve words in HDG(I) is ******.

For IFLOW = 2

For the axisymmetric flow field, the first three records consist of title information and constituent identification:

Record 1	Words 1, 12	(HDG(I),I=1,12)	Flow field problem title. For information only.

INPUT/OUTPUT TAPES (Continued)

Record 2	Words 1,4	(BETA(I),I=1,4	Propellant or gas title. (For information only.)
Record 3	Word 1	NOCON	Number of constituents on the flow field tape.
	Words 2,3	(KONAME(I,J), J=1,2)	Name of the Ith constituent. Consists of two A6 words.
	Word 4	CONWT(I)	Constituent molecular weight.
	Word 5 and subsequent - Repeat words 2 thru 4 for I = 1, NOCON		

The remainder of the case consists of two-record groups specifying the gas data.

Record 4	Word 1,3	NOPS	Number of radial values for property data at this Z-plane. This is repeated 3 times.
	Word 4	LS(I)	When ISHOCK =-1, this value must be the (L) index of the radial point just inside the shock. If ISHOCK ≠ -1, NØPS may be repeated here to maintain proper record length.
	Word 5	ZZ(I)	Z-coordinate of the data presented in the next record.
Record 5	Word 1	R(I,L)	Radius
	Word 2	T(I,L)	Temperature
	Word 3	P(I,L)	Pressure
	Word 4	FF(L,J), J=1,NOCON	Mole fraction. Repeated for J=1,NOCON.

The word group above (Record 5) is repeated on this record for L=1,NOPS.

Sets of records like 4 and 5 are repeated until all the data is loaded. The end of the flow field is signaled by a record with NOPS = 0.

INPUT/OUTPUT TAPES (Continued)

For IFLOW = 3

For the three-dimensional flow field, the first three records consist of title information, flow field geometric parameters, and constituent identification.

Record 1	Words 1, 12	(HDG(I),I = 1,12)	Flow field problem title. For information only.
Record 2	Words 1, 4	(BETA(I),I = 1,4)	Propellant or gas title. (For information only).
	Word 5	ISYMSC	Flow field geometry option.
	Word 6	HANG	Half angle of symmetrical sector used in flow field geometry.
	Word 7	CTCD	Outboard engine spacing from vehicle centerline.
Record 3	Word 1	NOCON	Number of constituents on the flow field tape.
	Words 2,3	(KONAME(I,J),J=1,2)	Name of the Ith constituent. Consists of two A6 words.
	Word 4	CONWT(I)	Constituent molecular weight.
	Word 5 and subsequent - Repeat words 2 thru 4 for I = 1,NOCON		

The remainder of the case consists of groups of three records specifying the gas data.

Record 4	Word 1	ZZ(I)	Z coordinate of the data in the following records.
	Word 2	NETAS	Number of η -values to be specified at this Z-plane.

INPUT/OUTPUT TAPES (Continued)

Record 5 and 6 are repeated for J = 1, NETAS

Record 5	Word 1	ETA(I,J)	Value of η at the Jth position.
	Word 2	NOPS	Number of radial points for gas property values at this η -position.
	Word 3	LS(I,J)	When ISHOCK = -1 this value must be the (L) index of the radial point just inside the shock. If ISHOCK $\neq$-1, NOPS may be repeated here to maintain proper record length.
Record 6	Word 1	R(I,J,L)	Radius
	Word 2	T(I,J,L)	Temperature
	Word 3	P(I,J,L)	Pressure
	Word 4	FF(L,N),N = 1,NOCON	Mole fraction. Repeated for N = 1, NOCON.

The word group (Record 6) above is repeated on this record for L = 1, NOPS.

Sets of records like 4 thru 6 are repeated until all the data is loaded.

The end of the flow field is signaled by a record with NETAS = 0.

Line of Sight Tape

Density - 800 BPI FORTRAN IV Binary Input or output on Logical 10

This tape is generated by the flow field subroutines and can be used as an input tape with IFLOW = 1. The primary purpose for saving this tape is to allow restart and completion of a radiation calculation that has been terminated by the estimated run time limit. It can also be used to rerun a problem with reduced integration limits. However, in this case DS must not

INPUT/OUTPUT TAPES (Continued)

be changed and the values of θ and ϕ for the lines of sight must match those existing on the tape. The first several records consist of input data which is defined in previous Section on input cards.

Logical record one consists of 37 + NOKON words in the following order:

Word 1 KASE	Word 15 SMAX	Word 29 TANGLE
2 DATE	16 DS	30 ENUI
3 IFLOW	17 XP	31 ENUF
4 HDG	18 YP	32 DENU
5 BETA	19 ZP	33 TDIFF
6 IUNITS	20 IPLANE	34 ACMIN
7 IZI	21 NOKON	35 SZERO
8 IZF	22 IBLOCK	36 (NUMCON(K),
9 THETAI	23 ICARB	K = 1,NOKON)
10 THETAF	24 ISHOCK	
11 DIHETA	25 ISCALF	
12 PHII	26 HANG	Word (36 + NOKON) ISYMSC
13 PHIF	27 CTCD	Word (37 + NOKON) KCARB
14 DPHI	28 RSCAL	

The geometric scaling data is listed in the second record. It consists of 9 words as follows:

Word 1 RSCAL	Word 4 F1SCAL	Word 7 F4SCAL
2 TSCAL	5 F2SCAL	8 F5SCAL
3 PSCAL	6 F3SCAL	9 F6SCAL

INPUT/OUTPUT TAPES (Continued)

Logical record three gives the orientation of the plane of interest and will consist of either one or nine words depending upon IPLANE.

If IPLANE = 0

Word 1 OMEGA

If IPLANE = 1

Word 1	ULX	Word 4	VLX	Word 7	WLX
2	ULY	5	VLY	8	WLY
3	ULZ	6	VLZ	9	WLZ

Logical record four lists the constituent names used for this case. Each constituent name is two A6 words.

Word 1	KON (1)
↓	↓
(2*NOKON)	KON (2*NOKON)

The remainder of the input data may require from 1 to 173 additional records depending upon the input options chosen. Up to 151 records may be required for specifying the addition of carbon particles to the plume (ICARB > 0). The blocking circle specifications requires one record if IBLOCK > 0, and the specification of shock radii, for ISHOCK =1, may require up to 21 records. The arrangement of the records and the dependence upon the options chosen are outlined below.

The number of records required for adding carbon particles to the flow field depends upon the values of ICARB and IFLOW.

If ICARB = 1, one record with two words is used.

Word 1 FC (1,1,1)

2 CRATIO (1,1,1) - This word not required, but is written for convenience

INPUT/OUTPUT (Continued)

If ICARB = 2, two to eight records may be used.

Record 1	Word 1	ZZFC (1)	This is not required under this option, but is written here to simplify routines.
	2	NOETAC (1)	For IFLOW = 2, this is set equal to 1
Record 2	Word 1	ETAC (1,L)	This is required for IFLOW = 3 only
	2	NOPSFC (1,L)	
Record 3	Word 1	FC (1,L,K)	Sets of FC and CRATIO are repeated for K = 1, NOPSFC (1,L)
	2	CRATIO (1,L,K)	

Records 2 and 3 are repeated for L = 1, NOETAC(1).

If ICARB = 3, up to 151 records may be used.

Record 1	Word 1	NZFC	
Record 2	Word 1	ZZFC(I)	
	2	NOETAC(I)	Set = 1 for IFLOW = 2
Record 3	Word 1	ETAC(I,L)	Required for IFLOW = 3 only, but written in all cases for simplicity
	2	NOPSFC(I,L)	
Record 4	Word 1	FC(I,L,K)	Sets of FC and CRATIO are repeated for K = 1, NOPSFC(I,L)
	2	CRATIO(I,L,K)	

Records 3 and 4 are repeated for L = 1, NOETAC (I)

Records 2 thru 4 are repeated for I = 1, NZFC

INPUT/OUTPUT TAPES (Continued)

The record for the blocking circle specifications consists of IBLOCK groups of 6 words each.

Word 1	XC(I)	
2	YC(I)	
3	ZC(I)	
4	RC(I)	
5	KIND(I)	
	This word group is repeated for I = 1, IBLOCK.	

The number of records required for listing the shock radii when ISHOCK = 1 depends upon the flow field geometry. If IFLOW = 2, only two records are used, but if IFLOW = 3, up to 21 records may be required.

Record 1	Word 1	NZSH	
	2	IZSH	
	3	NOETAS(I)	This word is repeated for I = 1, NZSH. This information is not required for IFLOW = 2, but words are placed on the record as shown.

If IFLOW = 2 only one more record is required

Record 2	Word 1	RSHOCK (I,1)	This word is repeated or I = 1, NZSH

If IFLOW = 3 the number of additional records is equal to NZSH.

Record 2	Word 1	RSHOCK(I,J)	This word is repeated for J = 1, NOETAS(I)

Record 2 is repeated for I = 1, NZSH.

This concludes the records specifying input data. Following these records, are a number of records equal to the number of lines of sight in the problem

INPUT/OUTPUT TAPES (Concluded)

plus 1. The final record signals the end of the problem by having LSET = 0. The words in each record are as follows:

Word 1	LSET	Number order of the line of sight
2	LPT	Number of points on the line of sight
3	LBLOCK	Blocking index
4	SINKO	Product of $\sin\theta \cos\theta$
5	THETA	Angle θ
6	PHI	Angle ϕ
7	DSFACT	Differential angle factor ($\sin\theta \cos\theta \, d\theta d\phi/\pi$)
8	DX	Integration increment on X coordinate
9	DY	Integration increment on Y coordinate
10	DZ	Integration increment on Z coordinate
11	SMIN	Upper limit of the s summation
12	XT(L)	X coordinate
13	YT(L)	Y coordinate
14	ZT(L)	Z coordinate
15	TWT(L)	Temperature
16	PWT(L)	Pressure
17 to (16+NOKON)	FWT(L,K)	Mole fraction. This is repeated K = 1, NOKON

Words 12 thru (16+NOKON) are repeated for L = 1, LPT.

Final Word	DPHI	Integration increment for ϕ

PRINTED OUTPUT

The initial section of output is printed in the FLOUT subroutine. It consists of: the problem and flow field identification, the unit system for input, the limits of integration, and the coordinates of the point of interest. Following this, the inclination angle OMEGA or the nine directional cosines (ULX ---- WLZ) are output to define the orientation of the plane containing the point of interest. Then the constituents which will be considered are listed. After this, the output depends upon the options chosen. If ICARB is greater than 0, the desired carbon particle distribution is listed. Following this, the blocking circle specifications are listed if IBLOCK is greater than 0. Then the shock radii data are output if ISHOCK is greater than 0. Finally, this section of output is completed by printing the geometric scale factors if ISCALF is greater than 0.

The second section of output is printed in FLOW2D or FLOW3D if IFLOW is greater than 1. If IFLOW is less than or equal to 1, this section of output is omitted. The output quantity depends upon the option NFLOW. If NFLOW = 1, the radius (R), temperature (T), pressure (P), and constituent mole fractions (F1 to F6) at each point in the flow field are listed. If NFLOW = 0, only the first and last radial points are listed to assure proper input operation.

The third section of output is printed in ACDATA. This section lists the absorbtion coefficient and line density data which will be used in the program. If NABS = 0, only the first and last entry for each constituent are listed to minimize output while assuring proper program operation . If NABS = 1, all values for each constituent will be listed.

PRINTED OUTPUT (Continued)

The fourth section of output is printed in either MODL3A or MODEL3, depending on the value of IRAD. The output depends upon the option NLINE. If NLINE = 0, the integrated irradiance ($\dot{q}/A$ or FLUX) is printed after the integration over each $\Delta\theta$ step is complete. When NLINE = 1, the output is printed for each line of sight. In this case, the value of θ (THETA) and ϕ (PHI) for each line of sight is listed along with the following data:

OUTPUT LABEL	MNEMONIC*
SHAPE FACTOR - DELTA	DSFACT
SUM	SFACT
FLUX - DELTA	LOSFLX
SUM	FLUX
RADIANCE - LINE OF SIGHT	RADLOS
- AVERAGE	RADAVG

In addition to the above data, the output will note which lines of sight missed the gas plume and which lines of sight were blocked by blocking circles before entering the gas plume. For the lines of sight which miss the gas, DX, DY, and DZ are printed to indicate the direction of the line of sight.

The output in the fourth section is similar for NLINE = 2 or 3. In both cases the coordinates for the position on the line of sight are listed along with the gas properties, number of Δs steps, incremental and summed irradiance, and average transmissivity. The difference between NLINE = 2 or 3 is that for NLINE = 2 the output is printed at the end of each integration step (DSS),

---

* MNEMONICs are defined in APPENDIX A.

PRINTED OUTPUT (Continued)

while with NLINE = 3, the output is printed at each geometric step (DS) along with the average values for each integration step. Due to the storage allocation system used in MODEL3, only the data for the first spectral interval along the line of sight will be printed. The computer names corresponding to the output labels are listed below:

OUTPUT LABEL	MNEMONIC
X	X
Y	Y
Z	Z
X	X
T	TW
P	PW
F1 thru F6	FW(1) thru FW(6)
DS STEPS	JFK
FLUX-FOR DS	DSFLUX
-SUM	LOSFLX
AVG - G	AVGG

At the beginning of the line of sight, the output values of θ and ϕ for the line of sight are listed, and at the end of the line of sight the following data is printed.

OUTPUT LABEL	MNEMONIC
SHAPE FACTOR - PLUME	SFACT
TOTAL	TSFACT
FLUX - TOTAL	FLUX
LOS	LOSFLX
RADIANCE - AVG	RADAVG

PRINTED OUTPUT (Continued)

OUTPUT LABEL	MNEMONIC
PATH LENGTH FOR H2O	UH2O
CO2	UCO2
CO	UCO
C1	UCARB
HCL	UHCL
HF	UHF

When the integration is complete, the following output is printed regardless of the value of NLINE:

OUTPUT LABEL	MNEMONIC
NUMERICAL PLUME SHAPE FACTOR	SFACT
NUMERICAL TOTAL FACTOR	TSFACT
EXACT TOTAL SHAPE FACTOR	TRUESF
PLUME RADIANCE	RADPLM
OVERALL RADIANCE	RADAVG
TOTAL FLUX	FLUX

The final output item in the fourth section is the calculation time for the radiation calculation.

The fifth section of output data is printed in SPCOUT. It provides for spectral output and plotting. The printed spectral data is output when NSPEK >0. In the spectral output, some of the output data is modified to

PRINTED OUTPUT (Continued)

different units. Therefore, some of the output items listed below will be redefined.

OUTPUT LABEL	MNEMONIC	DEFINITION
WAVENUMBER	ENU	Wavenumber - 1/cm
WAVELENGTH	ELAM	Wavelength-microns (=10^4/ENU)
IRRADIANCE-WATTS/CM-STER	SFLXTO(L)	Spectral radiance per unit wavenumber. NSPEK = 11 or 12
-WATTS/CM	SFLXTO(L)	Spectral irradiance per unit wavenumber NSPEK = 13 or 14
-WATTS/SQ-CM-MICRON-STER	SFLXTO(L)	Spectral radiance per unit wavelength. NSPEK = 1 or 2
-WATTS/SQ-CM-MICRON	SFLXTO(L)	Spectral irradiance per unit wavelength. NSPEK = 3 or 4

The following data is for the last line of sight only.

G	GNEW(L)	Transmissivity
OPTICAL DEPTH	OD(I)	Optical depth for all constituents -math symbol $X(s,\omega)$.

The following data is output only if NSPEK = X2 or X4.

CONSTITUENT IDENTIFICATION	KON(I)	Constituent name for data on this line
DSTAR	FO(I) or DSTAR	Optical depth-math symbol X*.
D/DSTAR	DODST	Optical depth ratio for the constituent indicated -math symbol X/X*

PRINTED OUTPUT (Concluded)

OUTPUT LABEL	MNEMONIC	DEFINITION
DC/DSTAR	DCODST	Collision broadened optical depth -math symbol X_C/X^*
DD/DSTAR	DDODST	Doppler broadened optical depth -math symbol X_D/X^*
AC	AC	Collision broadened fine structure parameter -math symbol $\bar{a}_C$
AD	AD	Doppler broadened fine structure parameter -math symbol $\bar{a}_D$

When IRAD>0 and NSPEK = X2 or X4, the detailed spectral output must be limited because of storage limitations. This will occur when (ENUF-ENUI)/DENU * IRAD > NUDIM (NUDIM is set at 840). If the storage limit is exceeded, only a portion of the spectral data at the larger values of ENU will be output.

DIAGNOSTICS

If the number of line groups (IRAD) exceeds 10, the program will stop and print

NUMBER OF LINE GROUPS EXCEEDS THE MAXIMUM ALLOWED VALUE OF 10.

If the number of spectral intervals exceeds 440, the program will stop and print

(ENUF-ENUI)/IDENU+1 IS GREATER THAN THE MAXIMUM NUMBER OF SPECTRAL INTERVALS DIMENSIONED (440) . CASE TERMINATED.

If the flow field case to be read from tape cannot be found on the tape, the program will return to read the next data and write

*****SORRY, CASE XXXXXXXXXX IS NOT ON THIS TAPE. RUN TERMINATED.

If the flow field from tape does not contain the desired constituents, the program returns to read new data and writes

*****CASE NUMBER XXXXXXXXXX DOES NOT CONTAIN THE CONSTITUENT 'XXXXXXXXXXX'

If an input constituent cannot be identified by the program, the program returns to read new data and writes

THE CONSTITUENT-XXXXXXXXXXX-IS NOT RECOGNIZED BY THE PROGRAM. CHECK AGAINST NAMES IN THE IDENTC LIST.

If NZFC exceeds 10, the program will return to read new data and write

NUMBER OF CARBON Z-CUTS EXCEEDS 10

If NOETAC(I) exceeds 7, the program will return to read new data and write

NUMBER OF CARBON ETA-CUTS EXCEEDS 7. NOETAC(XXX)=XXX

If NOPSFC(I,L) exceeds 10, the program will return to read new data and write

NUMBER OF CARBON RADIUS POINTS EXCEEDS 10 NOPSFC(XXX,XXX)=XXX

If the number of Z-planes for shock radii exceeds 20, the program will return to read new data and write

NUMBER OF SHOCK RADIUS Z-CUTS EXCEEDS 20.

DIAGNOSTICS (Continued)

If the number of η-values for shock radii exceeds 13, the program will return to read new data and write

NUMBER OF SHOCK RADIUS ETA-CUTS EXCEEDS 13. NOETAS(XXX)=XXX

If IFLOW=1 and the input value of SMAX exceeds that on tape 10, the program will return to read new data and write

INPUT SMAX XXXXX.XX EXCEEDS LOS TAPE VALUE OF XXXXX.XX

If IFLOW=1 and the input value of DTHETA does not agree with that of tape 10, the program will return to read new data and write

INPUT DTHETA XXXXX.XX NOT EQL LOS TAPE VALUE OF XXXXX.XX

If IFLOW=1 and the input value of DPHI does not agree with that on tape 10, the program will return to read new data and write

INPUT DPHI XXXXX.XX NOT EQL LOS TAPE VALUE OF XXXXX.XX

If IFLOW=1 and the θ limits input exceed those from tape 10, the program will return to read new data and write

THETA LIMITS DO NOT AGREE - INPUT VALUES ARE THETAI=XXXXX.XX AND THETAF= XXXXX.XX LOS TAPE VALUES ARE THETAI=XXXXX.XX AND THETAF=XXXXX.XX

If IFLOW=1 and the ϕ limits input exceed those from tape 10, the program will return to read new data and write

PHI LIMITS DO NOT AGREE - INPUT VALUES ARE PHII=XXXXX.XX AND PHIF=XXXXX.XX LOS TAPE VALUES ARE PHII=XXXXX.XX AND PHIF=XXXXX.XX

If the number of line of sight points exceeds the maximum allowed, the program will return to read new data and write

NO. OF LINE OF SIGHT POINTS EXCEEDS XXXX, NEED LARGER DELTA S

If it is necessary to delete radial flow field properties to fit within storage limitations, the program will write the following warning and continue

*****RADIAL POINTS WERE DELETED FROM THE FOLLOWING DATA. NRMAX=XXXXX NOPS=XXXXX

If the flow field exceeds the maximum Z-plane at which the carbon mole fraction is specified when ICARB=3, the carbon mole fraction will be omitted, and the program will write

**********NO CARBON MOLE FRACTION SPECIFIED FOR Z=XXXXX.XX

DIAGNOSTICS (Concluded)

If the number of η-values exceeds 13 when IFLOW=3, the program will stop and write

NUMBER OF ETA-CUTS EXCEEDS 13. NETA(XXX)=XXX

If the absorption coefficients are being modified and the number of entries in the coefficient table (COEF(I,K)) exceeds the maximum allowed, the program returns to read the next case and writes

LAST COEF INDEX OF XXXXX EXCEEDS THE MAXIMUM ALLOWED VALUE OF XXXXX

If the optical depth is negative, the transmissivity is taken to be equal to that at the previous line of sight increment and the program writes the following warning

*****NEGATIVE DMO AT NU=XXXXXX. DMO=XX.XXXXE±XX

If the temperature is negative at any point, the following warning will be written

******WARNING - NEGATIVE TEMPERATURE ENCOUNTERED AT LSET=XXXXX LOSPT=XXXXX

If the number of spectral intervals summed over all the constituents exceeds NUDIM, the program returns to read new data and writes

*****THE SUM OF SPECTRAL INTERVALS FOR ALL CONSTITUENTS IS XXXX. THE MAXIMUM ALLOWED IS XXXX.

In order to assure that the plot section of the program was reached, the following statements will be printed at appropriate locations

BEGINNING PLOT SECTION
END OF PLOT SECTION

If the abscissa indication is missing for a plot, the program will skip to the next plot and write

ABSCISSA INDICATION MISSING

If the ordinate indication is missing for a plot, the program will skip to the next plot and write

ORDINATE INDICATION MISSING

If an input error calls for a plot of the fine structure parameters for carbon particles, the plot will be skipped and the following message will be written

FINE STRUCTURE PARAMETERS NOT USED FOR CARBON. PLOT XXX DELETED

PLOTS GENERATED

The number of plots generated will be equal to the input option NPLOT. The data plotted and the ordinate and abscissa descriptions will vary depending upon the specifications set forth by NSPEK (input card 2) and JPLOT (input card 32). The first digit of JPLOT specifies the abscissa variable and the second two digits specify the ordinate variables. The arrangement used is defined in the table below:

Abscissa Selection (First Digit)

JPLOT	Abscissa
1XX	Wavenumber (ENUV(I))
2XX	Wavelength (ELAMV(I))

Ordinate Selection (Second and Third Digits)

JPLOT	NSPEK	Ordinate
X10	01 or 02	Spectral radiance per unit wavelength watts/cm^2-μ-sr
	03 or 04	Spectral irradiance per unit wavelength watts/cm^2-μ
	11 or 12	Spectral radiance per unit wavenumber watts/cm^2-sr-cm^{-1}
	13 or 14	Spectral irradiance per unit wavenumber watts/cm^2-cm^{-1}
X20		Transmissivity (GNEW(L))
X3X		Optical depth for the weak line limit (FO(I))
X4X		Collision broadened fine structure parameter (a_C) averaged over the path.
X5X		Doppler broadened fine structure parameter (a_D) averaged over the path.

PLOTS GENERATED (Concluded)

Ordinate Selection (Continued)

XX1	Water vapor
XX2	Carbon dioxide
XX3	Carbon monoxide
XX4	Hydrogen chloride
XX5	Hydrogen flouride
XX6	Reserved for future addition.
X37	Optical depth for carbon particles (FOC(I))

NOTE: For all cases with JPLOT = X10, the plotting variable is a modified form of SFLXTO(I). For all cases with JPLOT > X10, the data is for the final line of sight only.